MEASUREMENT AND MODELING OF THE HYDROLOGY OF CYPRESS WETLANDS - PINE UPLANDS ECOSYSTEMS IN FLORIDA FLATWOODS

By

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This dissertation is dedicated to my parents, brothers and sisters at home, who encouraged me to reach high . . .

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MEASUREMENT AND MODELING OF THE HYDROLOGY OF CYPRESS WETLANDS - PINE UPLANDS ECOSYSTEMS IN FLORIDA FLATWOODS

By

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The goals for this dissertation were to document the hydrology of cypress wetlands-pine uplands ecosystems in north central Florida and develop a simulation model (FLATWOODS). Three cypress wetland/pine upland systems embedded in a flatwoods landscape were extensively instrumented and monitored. Annual average canopy interception rates on a monthly basis for cypress wetlands and pine uplands were 12% (8-40%) and 14% (6-43%) of rainfall, respectively. An quantitative index was presented to describe the high dynamics of wetland hydroperiod. Groundwater table fluctuations were classified into four categories. Shallow groundwater flow velocity was low (<10 cm/day) due to low hydraulic gradients (<1.0 %), although the soil hydraulic conductivity was high (0.5-20 m/day). Groundwater flows followed the overall topographic gradients during the wet seasons, while during the spring transition season from wet to dry conditions, surface

water tended to recharge the surrounding uplands for some distance. Surface runoff was generated only from saturated variable source areas (VSA) associated with cypress wetlands in winter. The VSA increased 8-32% in a single storm. Monthly water balances showed that rainfall and/or surface inflow were the major inputs to the wetland/upland ecosystems, while ET and surface outflow were the main outputs.

The existing COASTAL model with the following modifications was used to construct the FLATWOODS model: 1) algorithms for the calculation of initial soil moisture content in unsaturated zones were added; 2) algorithms for unsaturated water drainage from unsaturated zone to the surficial aquifer were modified; 3) evapotranspiration procedures were modified by adding plant leaf area index (LAI) and root components; 4) soil evaporation was set as a function of groundwater table depth and LAI; 5) smaller grid systems, dynamic aquifer parameters of hydraulic conductivity and specific yield were employed to account for the surface-groundwater interactions; and 6) surface flow routing procedures for each modeling unit were added. In addition, FLATWOODS was calibrated and verified with field data of ground water table and daily runoff from two different research sites.

Simulation by the FLATWOODS model showed that clear-cutting both pine uplands and wetlands had the greatest effect on groundwater table and runoff, especially during the first six years after treatment. Following the regrowth of young plantations, the hydrologic regime may recover to the pre-treatment conditions within about ten years. Partial harvesting of wetlands or uplands significantly reduced hydrologic impacts in pine flatwoods. Forest harvesting had the most pronounced effects on groundwater tables during dry periods.

CHAPTER 1
INTRODUCTION

Research Background

In modern times, environmental quality has become an important component of national concern. Protection of the environment and wise use of natural resources have never been so frequently addressed by the governments as well as citizens, in developed countries as well as in developing countries on this planet. In the USA, the environmental influences of forest changes were hypothesized by Noah Webster as far back as 1799 (Kittredge, 1948). The book "Man and Nature" , and its later version "The Earth as Modified by Human Action" (Marsh, 1965; Marsh; 1884) has been regarded as the most comprehensive summary of the viewpoints on human activities, including forest water relations, during that time. With the advancement of modern technology, mankind has increasing powers to alter abiotic as well as natural biotic systems. For example, more mechanical and automated equipment is available for silvicultural practices such as harvesting, roading and ditching. Fertilizer, pesticide, and herbicide use for vegetation management have become nearly routine not only in agricultural fields but also on forest lands. In Florida, tourism has been one of the major sources of income for the State, and this industry has imposed a high priority and more pressure on natural resources conservation. With the great increase of population and the demands for pulp and fiber, the price of commercial forests increased rapidly. Forest

management practices with near-agricultural intensity (short rotation, clear-cutting, burning, fertilization) have been adopted to gain more yield per unit land area. Forest lands are no longer seen as 'pure green' lands without any environmental problems, but are listed as one of the sources of non-point pollution along with agricultural and urban lands (Binkley and Brown, 1993). Since the 1970s, values of forested wetlands have been recognized in terms of timber production, water quality protection and flood control, and wildlife habitat. On a global scale, wetlands may be significant in balancing nitrogen, sulfur, carbon and other important elements in the biosphere (Mitsch and Gosselink, 1986). Protection of biodiversity as well as forest environments characteristic of unique ecosystems have been the major additional goals of the recent forest ecosystem management perspective (Greenburg, 1993). Conflicting strategies over the same lands have generated many concerns among environmental protection agencies as well as forest industry companies about the degradation of environmental quality, and consequently forest productivity in the long run.

In 1975, with the goal to evaluate the ecological effects of silvicultural practices commonly employed in the southeastern United States, the Intensive Management Practices Assessment Center (IMPAC) in Florida was formed in a cooperative effort by the University of Florida's School of Forest Resources and Conservation (SFRC), the U.S. Forest Service's Southeastern Experiment Station, and various members of the regional forest industry. A research site was located in Bradford County and watershed experiments have been conducted since 1978. In 1991, in recognizing that little data were available on the influence of different forest management practices on wetlands in pine flatwoods

ecosystems, a research project with emphasis on the water flow relations between cypress wetlands and slash pine uplands was initiated by the Soil and Water Sciences Department and the SFRC with funding from the National Council of the Paper Industry for Air and Stream Improvement (NCASI). The author has assisted in both the IMPAC project and NCASI wetland studies in field measurement and hydrologic model development since 1991.

Due to the hydrologic characteristic of high variability in space and time, the delayed forest ecosystem response to disturbance, and the long life cycle of trees, it usually takes a long observation time to make definitive conclusions. Computer simulation techniques provide alternative ways to help solving environmental problems (Freeze, 1971; Swift et al., 1975; Mercer and Faust, 1980; Decoursey, 1985). Our approach to hydrologic studies of flatwoods has been comprehensive, including both extensive field measurements in the NCASI and the IMPAC sites for detailed information of each hydrologic component and its processes, and computer modeling based on field parameters. The ultimate goals for developing a simulation model were to achieve improved understanding of forest ecosystem and provide a scientific basis for forest water management.

Objectives

This dissertation study focused on hydrologic dynamics of the shallow groundwater table and evapotranspiration in pine flatwoods landscape emphasizing surface-subsurface (ground water) water interactions, and hydrologic continuity of wetland-upland systems within variable source areas (VSA). The goals of this study were to provide substantial evidence and establish scientific theories for evaluation of hydrologic effects of common

forest management practices on wetland/upland systems, and therefore to provide basic information for forest ecosystem management in pine flatwoods.

Hypotheses were as follows:

1. Pine flatwoods are heterogeneous hydrologic systems; cypress wetlands have a significantly different water regime from pine uplands.
2. Pine flatwoods are storage-based hydrologic systems; groundwater tables are controlling factors for surface flow in pine flatwoods and surface runoff is generated by the Variable Source Areas (VSA).
3. Rainfall and evapotranspiration are the major water input and output respectively, of pine flatwoods ecosystems.
4. Water movement in pine flatwoods ecosystems can be modeled adequately by a coupled surface-subsurface forest hydrological model.

Specific tasks were as follows:

1. Determine the surface-subsurface water flow pathways and variable source areas.
2. Quantify the water balances (precipitation, canopy interception, percolation, evapotranspiration, surface runoff and subsurface flows) of wetland-upland ecosystems;
3. Develop/adapt a distributed, multi-dimensional, process-based hydrologic simulation model for cypress wetland/pine upland systems in the flatwoods landscape. The model was intended to be used as a research tool to test the hypotheses for pine flatwoods hydrology and to project hydrologic effects of different forest management practices in wetland-upland systems.

Structure of the Dissertation

As described in the objectives of this dissertation, it essentially includes two integral parts; experimental data analysis and model development and testing. Chapter 2, Literature Review, identifies research needs in flatwoods hydrology, both with respect to field experimentation and computer simulation. Chapter 3, Experimental Methods, introduces the research sites where experimental data were collected for model development, and instrumentation and data analysis methods. Chapter 4 presents the field experimental results for each process (precipitation, soil moisture, water table dynamics, groundwater flow, surface water flow and deep seepage) of the complete hydrologic cycles of three replicate wetland-upland systems. The hydrologic processes were first analyzed separately and then combined by the water balance equation, and as a result, monthly water budgets were established for wetlands and uplands respectively. Chapter 5 introduces the theory behind the new computer simulation model - FLATWOODS, which is a modification of the published COASTAL model. Then the model calibration and verification results based on field data from two experimental sites, Gator Nationals Forest and Bradford Forest are presented. The model sensitivity analyses combined with model application to several scenarios of common forest management practices are presented in the last section of Chapter 5. In the Appendices, detailed water table maps and the FLATWOODS model program code are presented.

CHAPTER 2
LITERATURE REVIEW

Past studies relevant to flatwoods hydrology by experimental methods and selected modeling efforts for this landscape have been discussed in this review.

Experimental Field Studies

Wetland Hydrology Studies

Hydrogeology of cypress wetlands has been extensively studied by the Center for Wetlands and the Geology Department at the University of Florida over the past two decades, to investigate the feasibility of waste water treatment by wetlands (Cutright, 1974; Smith, 1975; Gillespie, 1976; Ewel and Odum, 1984). Those workers concluded that the water table aquifer and surface water of study sites in Alachua County were hydrologically isolated from the Floridan Aquifer. Furthermore, it was suggested that the major water discharge from wetlands was through evapotranspiration, and that wetlands could be recharge areas during wet periods but discharge areas during dry periods. Also, the integrity of hydrology, geology and biology of cypress domes and surrounding upland forests was recognized.

The study on cypress wetland hydrology by Heimburg (1976) has been widely cited in the literature and may be regarded as the only complete work on cypress dome hydrology

although most of the domes investigated were not under typical conditions due to the addition of artificial water sources. Surface water in cypress domes was concluded to be closely coupled with groundwater in surrounding pine uplands, and cypress swamps could be recharged or discharge water depending on the position of the surrounding groundwater table relative to the surface water level. Three groundwater flow patterns between ponds and their surroundings were postulated, namely flow-in, flow-out and flow-through, but only the last two types were documented. Riekerk (1992) employed a heat-pulse groundwater flow meter to directly measure groundwater flow velocity at the margins of cypress ponds and found tremendous variation both in space and time possibly due to fractal effects of forest soils. Although this method has an advantage over the Darcian gradient method in that it does not need the parameter of hydraulic conductivity, significant measurement errors may mask the relative low flow rates of groundwater in these systems. Phillips et al. (1993) and Phillips and Shedlock (1993) investigated the hydrologic relations between surface water and groundwater of small seasonal ponds in a forested Coastal Plain drainage basin in Delaware. They concluded that the groundwater table was not a subdued expression of land surface topography, and wetlands could behave as seasonal recharge or discharge areas. Hydrochemical sampling showed that the water quality of shallow seasonal ponds was strongly influenced by the adjacent groundwater systems with the upland-wetland margins as the most dynamic part. Winter and Carr (1980) documented flow-through type wetlands in a study in North Dakota. Ewel (1985) studied three cypress swamps in the Withlacoochee State Forest, central Florida, and found that average annual evapotranspiration (ET) was low at about 790 mm/year with a daily variation of 0.4-3.5 mm for the 3-year period during

which average annual rainfall was 1510 mm. It was implied that ET from cypress wetlands was lower than that from uplands and therefore that cypress ponds were beneficial for groundwater recharge (Ewel, 1990). Estimation of ET using daily hydrographs of water levels showed that the total water loss from cypress ponds was slightly lower than that from pine uplands (Ewel, 1993). Brown (1981) surveyed several cypress ecosystems in Florida to investigate how inputs of water and nutrients influenced the structure and functions of cypress wetlands. It was found that water loss from cypress forests increased with increasing phosphorus inputs. It was also found that transpiration rates from scrub cypress forests (1.0 mm/day) and cypress domes (3.1-3.8 mm/day) were lower than evaporation rates from open water bodies while those from the floodplain forests (5.6 mm/day) were similar. This suggested that cypress domes conserved water and used water more efficiently. Rushton (1994) reported that annual ET from a marsh with vegetation consisting of mainly pickerel weed and arrowhead in South Florida approximately equalled annual rainfall. Monthly ET was close to 80% of pan evaporation in the Spring and Fall but higher in the Summer, suggesting more water loss from wetlands than from open lakes without vegetation. Lake evaporation is often taken as 0.7*Class A pan evaporation measurements (Veihmeyer, 1964). By this definition, evapotranspiration from five experimental tanks covered with different aquatic plants, *Panicum regidulum*, *Juncus effusus, Carex lurida*, *Alternanthera philoxeroides*, and *Justicia americana*, were found 1.28, 1.22, 1.07, 1.01, 0.94 times evaporation from open lake water in the growing season (May-October) respectively (Boyd, 1987).

In a cypress wetland/pine upland mosaic system, it is not clear what part of the

intermediate areas would fall into a regulatory wetland definition due to a shortage of quantitative hydrologic information (Comerford et al., 1995; Segal et al., 1987). In general, wetland hydrologic information is relatively scarce compared to the other two criteria of vegetation and soils for wetlands delineation (Best et al., 1990). Wetland hydrology, the primary driving force in the formation and maintenance of wetlands, has been stressed as basic to understanding, quantifying and evaluating wetland functions and ecological processes (Ivanov, 1981; Gopal et al., 1982; Rykiel, 1984; LaBaugh, 1986; Gilvear et al., 1993). Carter et al. (1979) and Carter (1986) identified five areas of research for wetland hydrology studies:

1. The need for improving, refining, and perhaps simplifying existing techniques for hydrologic measurements;
2. The need for making accurate measurements of all the hydrologic inputs and outputs of representative wetland types and estimating the errors inherent in various measurement techniques;
3. The need to improve basic understanding and quantify the soil-water-vegetation relationships of wetlands;
4. The need to make detailed, long-term studies of different wetland types under different environmental conditions;
5. The need to continue developing models based on hydrologic data for a better analysis and predictive capability.

Upland Hydrology Studies

There is more literature on upland hydrology than wetland hydrology. The study by Asmussen and Thomas (1974) in a lower coastal site in Georgia documented overland flow as only 2% of the annual rainfall. The shallow phreatic aquifer was therefore a controlling factor affecting the behavior of the Coastal Plain streams. Sainju (1982) concluded that the surface of groundwater was relatively uniform and varied less than the associated topography, and that pine trees could benefit from groundwater for most of the studied area of pine flatwoods in north central Florida. In a similar site, Phillips (1987) studied soil water movement in a young flatwoods forest stand on a similar site and recognized an spatial heterogeneity of water tables due to even small topographic variations. This study suggested that two-dimensional models instead of one-dimensional models were needed to better represent water pathways in flatwoods. In a study on the hydrologic effects of adding treated sewage effluent in cypress ponds on surrounding soil moisture and nutrients, Okorie (1976) found 5 to 20 m from the pond edge of the treatment site had significantly higher soil moisture content at 30.5 cm depth, than the control (no sewage water). He suggested that the pond water treatment had significant influence on upland soil moisture. Most forest ecological studies have included hydrological components, because transpiration by plants and availability of soil water and nutrients are closely related to tree growth and forest productivity (Wickramasinghe, 1988; Gholz et al., 1990; Sands and Mulligan et al., 1990; McMutrie and Landsberg, 1992). These hydrologic components included soil water movement in the unsaturated zone and evapotranspiration. Annual transpiration of 110 cm

was recorded for a 25-year old slash pine stand in Florida (Golkin, 1981). Butler et al. (unpublished data, personal communication) compared estimates of ET from a mature slash pine forest by different methods including the Penman-Monthieth equation, Priestley-Taylor equation and a water table drop (WTD) method. ET estimated by WTD method generally was within the range of other methods, but the uncertainty of deep drainage and lack of soil moisture data in the unsaturated zone caused significant errors, especially when the water table was deep. Tremwel and Campbell (1992) investigated the hydrology and surface water quality of four pasture sites characteristic of Spodosols in the Okeechobee Basin during 1989-1991. Tremwel (1992) reported that the average surface runoff varied from zero (the plot with deep sandy soil) to 22% with an average of 11% of total rainfall. Annual ET calculated by the Penman-Monteith equation varied from 74% to 90% of rainfall, which amounted to 110 cm/year on the average. Capece (1984) studied the storm flow mechanisms by standard, widely used mathematical models. He concluded that flatwoods hydrologic systems were storage-based and that the groundwater table was crucial to predict runoff volume. Results of tracer experiments in pasture flatwoods showed that groundwater flow velocity was in the range of 1.9-12.0 cm/day and surface runoff dominated the transport mechanism for the relatively flat sites (< 0.3% land slope), while the groundwater flow was the primary mechanism at the sites with higher slopes (Capece, 1994).

Integrated Wetland-Upland Studies

Watershed-scale studies may be classified in the category of comprehensive studies of overall system responses to external disturbance. Significant field investigations in

hydrologic effects (water quantity and quality) of intensive forest management have been carried out for slash pine flatwoods systems since 1978 by the Intensive Management Practice Assessment Center (IMPAC) of the University of Florida (Riekerk et al., 1979; Rodriguez, 1981; Pratt, 1978). Three small artificially diked watersheds (Max., Min. disturbance and Control) were monitored for 17 years collecting weather, runoff, water quality and water table data at the Bradford Forest, 50 km north of Gainesville, FL. At the Gator Nationals Forest, 15 km north of Gainesville, FL, six small watersheds (plots) have been monitored to study the hydrologic and water quality responses to annual fertilization (Riekerk and Korhnak, 1984). At the University of Florida Austin Cary Forest, 13 km northeast of Gainesville, FL, two small watersheds were used as demonstration of forest management effects. Overall, it was documented that clear-cutting of 40-year-old flatwoods forests significantly increased runoff to 150 mm or 150% of predicted runoff in the first year. Water table levels were higher after harvesting due to reduced ET, and more pronounced effects were found when the water table was deeper in dry years (Riekerk, 1989). The runoff increase dropped to 65% in the 6th year. Annual average ET over a 5-year period from a young slash pine flatwoods watershed was estimated by an actual/potential ET ratio method as about 1050 mm, which was 82% of the total rainfall (Riekerk, 1989). However, these studies designed to evaluate the cumulative environmental effects of management practices and have given little attention to the heterogeneity of the system and hydrologic processes within the watersheds. The ongoing wetland/upland hydrology and evapotranspiration projects initiated in 1991 and 1992 by the National Council for Air and Stream Improvements (NCASI), the IMPAC and the U.S. Forest Service at the Gator Nationals

Forest may provide in-depth information on hydrologic dynamics in pine flatwoods, especially the interaction between wetland surface water and upland groundwater. Preliminary results showed that shallow groundwater flow generally followed the landscape gradients and most of the cypress wetlands were flow-through types, though local ground water flows may change direction during the annual dry-wet cycles (Crownover et al., 1995; Comerford et al., 1994; Sun et al., 1995). The implication of these experimental results was that management practices around wetlands may not be as problematic as surmised in terms of chemical loading to wetlands due to low groundwater flow rates and small source areas. A two-year study was focused on evapotranspiration of the slash pine plantations and associated cypress wetlands, and suggested there were no significant differences between these two ecosystems, but the composition of evapotranspiration (evaporation, transpiration and canopy interception) varied significantly between cypress wetlands and pine uplands (Riekerk et al., 1995). This study questioned the proposition that cypress wetlands conserved more water than uplands, and suggested that high variability of ET existed in cypress wetlands ecosystems. Different stand structures of pine plantations could also contribute to this variability.

Simulation Models

Although numerous forest hydrologic models currently exist in the USA and in the world, most of them cannot be directly applied to Florida's relatively flat terrain and have difficulty handling forested wetland-upland systems (Sun, 1985; Heatwole, 1986; Capece, 1984; Tremwel and Campbell, 1992). Selected existing forest hydrological models which

are relevant to the present study were compared and have been summarized in Table 2.1.

A simulation effort was made by Guo (1989) to test the applicability of the simulator VSAS2 to the pine flatwoods watershed at Bradford Forest for the prediction of stormflow. The simulation of five storm events showed that the original simulator significantly overestimated the peaks of the stormflow hydrographs. It was suggested that pond storage in this flat and complex landscape played a significant role in the runoff generation. Some models specifically developed for simulating high water table conditions in agricultural landscapes, such as CREAMS-WT (Heatwole et al. 1987), DRAINMOD (Skaggs, 1980, 1984), and FHANTM (Tremwel and Campbell, 1992), were applicable to horizontally relatively homogenous landscapes. How those models perform in spatially heterogeneous forested flatwoods is not known. Models developed to study wetland hydrology often included only the wetland itself without surrounding upland components (Hammer and Kadlec, 1986; Scarlatos and Tisdale, 1989; Kadlec, 1993b). Current ecological models to study water and nutrient or carbon fluxes in pine flatwoods employed a lumped approach, and placed significant emphasis on the vegetation components with various simplification of the soil components and water pathways in the ecosystems (Golkin and Ewel, 1985; Ewel and Gholz, 1991). A series of models have emerged to investigate the interactions between surface water and groundwater with various simplification in the evapotranspiration and unsaturated water movement in the hydrological systems (Winter, 1976; Cheng and Anderson, 1993; Wang et al., 1995)

In recent years, there is a tendency to develop more physically based distributed models (Beven, 1989; Jensen and Mantoglou, 1992; Bathurst and O'Connell, 1992;

Table 2.1. Selected forest hydrologic models.

NO	Title	Author	Distinct features
1	SHE (Systeme Hydrologique Europeen)	Abbott, 1986	Distributed physically based to simulate effects of human interference
2	WSHS (a mathematical model for the watershed hydrologic system)	Al-Soufi, 1990	3-D, physically based for soil-water-plant continuum
3	VSAS2	Bernier, 1982	Distributed, process based, stormflow. To test Variable Source Area Concept.
4	Peatland Hydrologic Impact Model-new version	Barten, 1989	Lumped, physically-based. peatland, upland hydrology simulated
5	BROOK2 (BROOK90)	Federer, 1983, 1995	Lumped forest hydrology model for the eastern USA
6	PROSPER	Goldstein, 1972	Lumped, process mixed soil-water-vegetation model
7	CREAMS-WT	Heatwole, 1987	Lumped, modified from CREAMS to apply to high water table condition in Florida
8	VS2DT (Variably Saturated, two Dimensional Transport)	Lappala, 1987	Physically based. Un- and saturated water and solute transport. It is being modified for wetland-upland system.
9	DRAINMOD-forest hydrology version	McCarthy, 1990	Lumped, subsurface drainage and runoff with high water table
10	MODFLOW	McDonald and Harbaugh, 1988	3-D distributed, physically based groundwater flow model
11	UNSAT2 -modified version	Neuman, 1974 Ahmad, 1991	2-D, un- and saturated finite element model; 2-D root distribution function included
12	A Distributed Numerical Model for Watershed Hydrology	Sabur, 1990	Distributed, physically based for low relief, infiltration & ET dominated areas
13	COASTAL-a distributed hydrological simulation model for lower coastal watershed in Georgia	Sun, 1985	2-D, most physically based, distributed model for flat terrain with high groundwater table; Coupling of MODFLOW and BROOK.
14	Hydrological Modeling Using Variable Sources Areas	Whitelaw, 1989	3-D, physically based, upgraded from VSAS2 and SHE
15	Hydrology-Vegetation Model	Wigmosta, 1994	Distributed, ET emphasized, surface-subsurface flow, large complex watershed to evaluate effects of the climate change
16	ANSWERS-forest hydrology version	Thomas, 1986	Distributed, nonpoint pollution
17	SWIF (Soil Water in Forested Ecosystems)	Tiktak, 1992	Lumped, soil moisture simulation for forest ecosystems in lowland areas
18	Integrated Surface Water and Groundwater Model	Yan and Smith, 1994	Distributed, modification of MODFLOW and South Florida Water Management Model

Wigmosta, 1991) and couple hydrologic processes with biological processes (Al-Soufi, 1987; Band et al., 1993; Wigmosta et al., 1994). This development has been driven by the need

for comprehensive large-scale (watershed to global) ecosystem studies, in which the hydrology is one of the most important components (Pierce et al., 1987), and accelerated by the increase of computation power. Another factor may be that more spatial field data are available with the aid of Geographic Information Systems (GIS). The Florida flatwoods landscape includes a mosaic of cypress wetlands and forest uplands, so the hydrology of flatwoods is inherently complex. Examples are the slight spatial changes in topographic elevation causing significant changes in the water regime, and obstructive soil layering because of the spodic and argillic horizons in the soil profile. The heterogeneous vegetation cover of wetlands and uplands and associated phenology may further complicate the interactions between surface water and groundwater. Due to the complex geologic formation of flatwoods, the preferential water pathways in this system have not been either well documented or understood. A new distributed flatwoods forest hydrologic model is needed to study the hydrologic processes of wetland/upland systems and provide a tool for water management, specifically for this landscape. It is worthwhile to mention that the South Florida Water Management District (SFWMD) has proposed a conceptual integrated hydrologic model for Dade County in south Florida characterized by flat topography, sandy soils, a shallow groundwater table, and well developed canal systems (Yan and Smith, 1994). The model was intended for use in regional planning for water supply, but no further action has been taken (Yan, personal communication, 1994).

CHAPTER 3
RESEARCH APPROACH

Basically two research approaches, experimental field studies and computer simulation methods, were used in this study. As in most cases, on the one hand, field experiments generate more realistic data but are limited by manpower and financial resources for studies of large-scale systems, while on the other hand, computer modeling methods are less costly but often restricted by available real data for calibration and verification. The design of this study is a compromise between these two approaches. Experimental field methods are introduced in this chapter, while simulation methods will be discussed in Chapter 5 along with model development.

Physical Setting, General Experimental Design and Instrumentation

Two research sites were selected as the basis for data collection for this study of typical flatwoods landscapes in north central Florida. One was the Gator Nationals Forest, located 15 km north of Gainesville in Alachua County (Figure 3.1). This 42-ha flatwoods site has been studied by several projects by different disciplines (Comerford, et al.1994; Riekerk et al., 1994). Another site is the Bradford Forest on industrial lands in Bradford County, about 50 km north of Gainesville, FL (Figure 3.1). There were three small watersheds on this site, which have been monitored by the IMPAC project since 1978 to

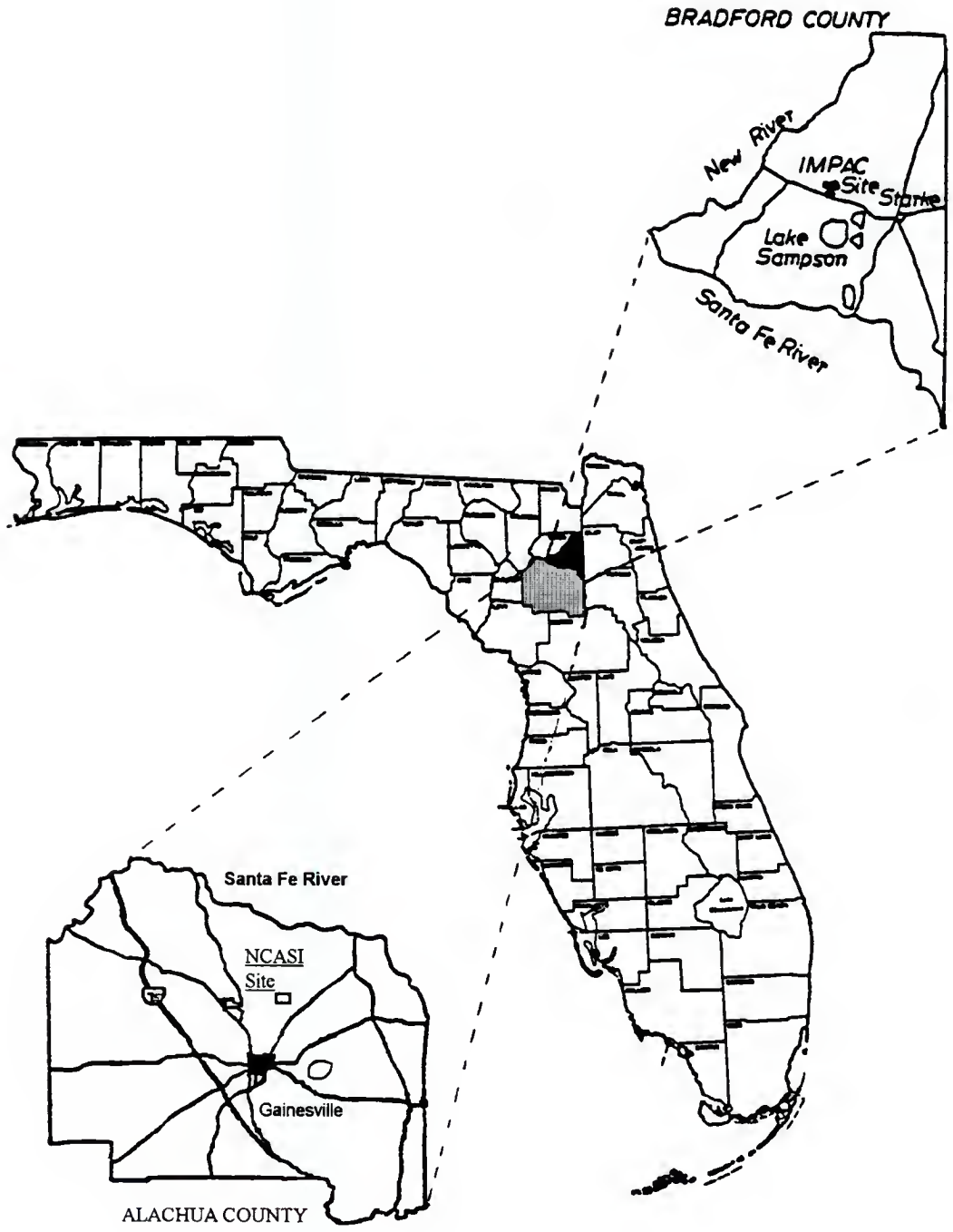


Figure 3.1. Location of the research sites in Florida

evaluate environmental effects of different forest harvesting methods (Riekerk, 1989). In this dissertation, wetlands refer to cypress domes or cypress ponds delineated by the saw palmetto line, while uplands refer to the surrounding thinned pine plantations. The saw palmetto line was defined as the distinct vegetation break from wetland vegetation to saw palmetto and slash pine plantations. The wetland margin area extends from the saw palmetto line out to about 25 m into the lower pine upland areas.

Gator Nationals Forest (GNF) Site

This site was located in the plateau physiographic region in Alachua County where Plio-Pleistocene terrace deposits and Hawthorne Formation dominate the geology. Topographical slopes ranged from 0 to 1.6% (Figure 3.2). Surface flow from this site generally was facilitated by ditches leading into interconnected wetlands which drained into the Santa Fe River to the north of Alachua County. The average annual temperature was 21°C, with a mean monthly low of 14 °C in January and high of 27 °C in July. Average annual rainfall was about 1330 mm with dry periods during the spring and the fall. The average monthly rainfall patterns during the study period from 1992 to 1994 and the 61-year average have been presented in Figure 3.3. A 50*50 meter grid system was overlaid over the entire 42 ha experimental area and each grid point was marked and labeled with a steel post and related to a reference coordinate (0, 0) set by an arbitrary elevation of 30.48 m (100 feet) above mean sea level. The actual topographical elevation of the study site was about 47 m above mean sea level. A shallow water table well was installed at every second grid point, and water table data have been collected on a biweekly basis since 1992. More

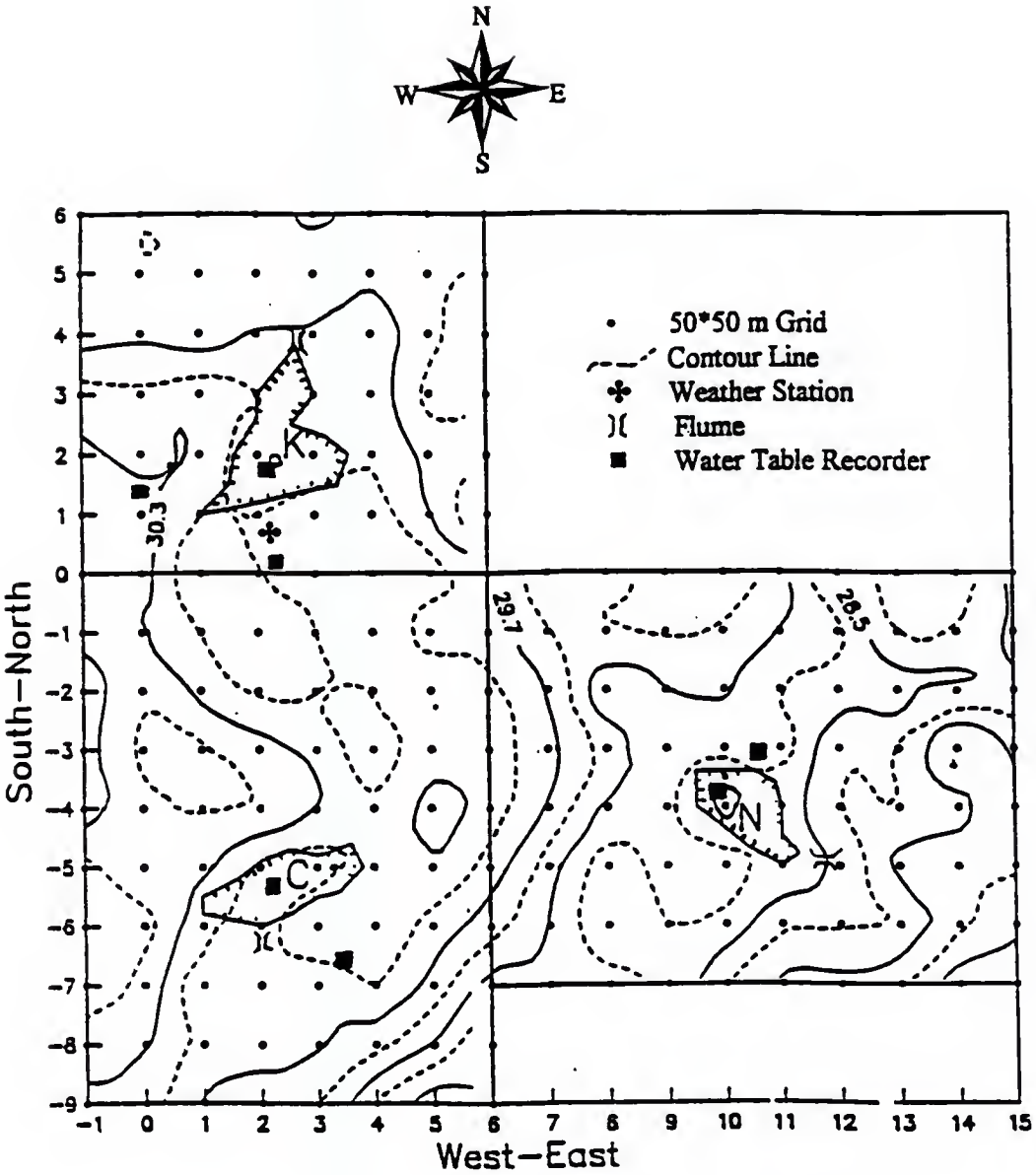


Figure 3.2. Topographic map of the Gator Nationals Forest site in Alachua County, Florida.

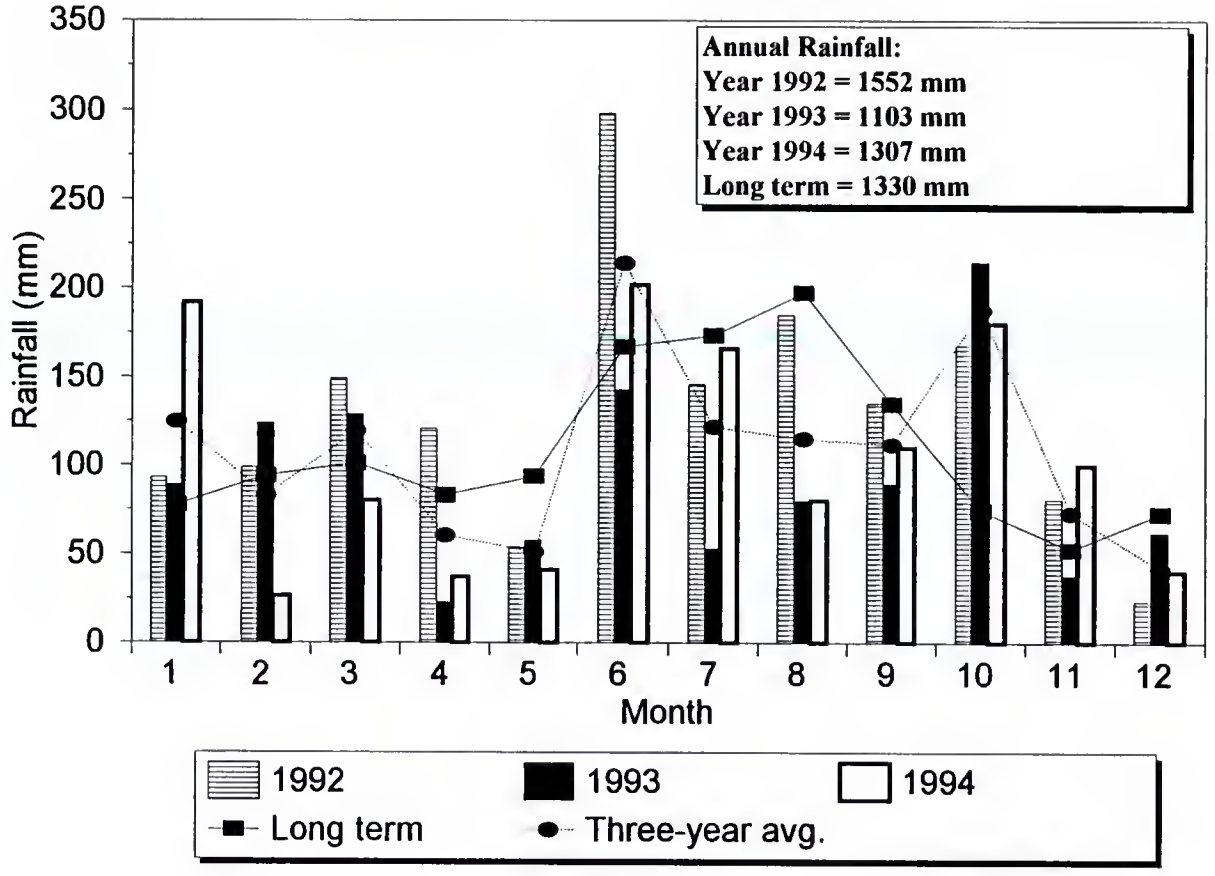


Figure 3.3. Monthly precipitation in 1992, 1993, 1994 at the GNF site and the long term average (1932-1992) of Gainesville, Florida.

detailed description of the site and instrumentation of the grid system can be found in the annual research reports submitted to NCASI (Comerford, 1993).

Approximately 35% of this 42-ha site was in cypress swamps with sizes ranging from a few square meters to more than 5 ha, while the remaining upland areas were in slash pine plantations. The 27-year-old upland plantations were 5th-row thinned in 1986 to a stem density of 500 stems/ha (Riekerk et al, 1992). Pond cypress (*Taxodium ascendens)* dominated the wetland species along with slash pine (*Pinus elliottii*) and black gum *(Nyssa sylvatica var. biflora*). The dominant tree canopy in uplands was slash pine with an understory of saw palmetto (*Serenoa repens*) and gallberry (*Ilex glabra*) shrubs. The geology of this site has not been investigated in detail although several bore holes were drilled in the ponds. However, the geologic characteristics and formation of cypress domes at similar sites in the region were extensively studied to determine the applicability of wetlands for waste water treatments (Cutright, 1974; Smith, 1975; Gillespie, 1976). The Austin Cary Control Dome located 5 km southeast of the GNF site was cited as representative of the geologic characteristics of a cypress wetland and its surrounding (Figure 3.4). It was suggested that the surficial aquifer consisted mainly of sands, and that the underlying 60-m thick Hawthorn Formation of white dolomite with phosphate pebbles and gray-green clays isolated it from the deep karstic Floridan Aquifer. At the GNF site, impermeable blue-green clays approximately 3-5 m below the bottom of the wetlands separated the shallow sandy water table aquifer from the underlying artesian secondary aquifer consisting of various materials such as clayey sand, sandy clay or permeable white dolomite. Generally, the soils in both wetlands and pine forests were coarse-textured and

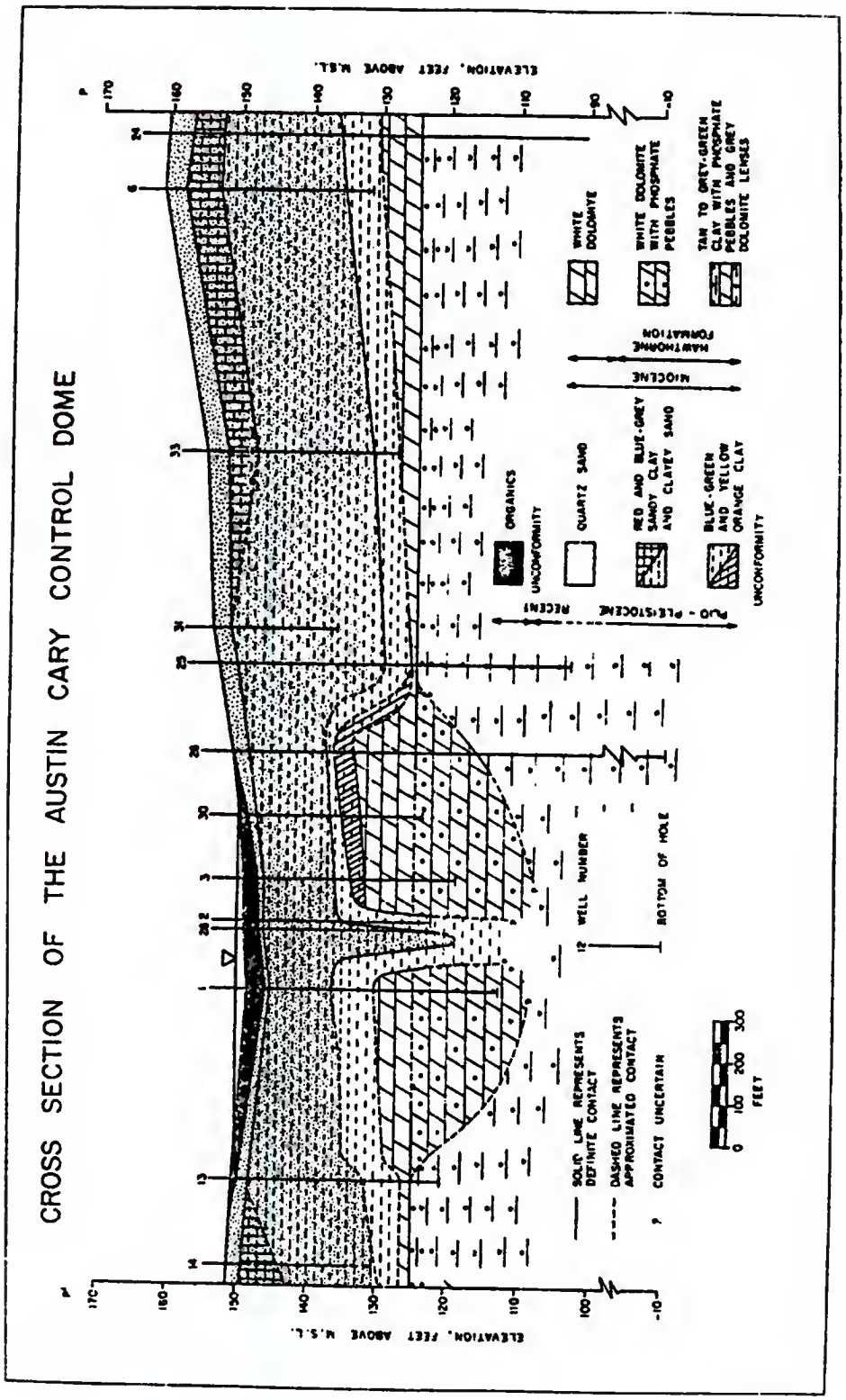


Figure 3.4. Geology of the Austin Cary Control Dome (Gillespie, 1976).

Table 3.1. Site characteristics and instrumentation at the Gator Nationals Forest site.

System	K	C	N
Surface areas of wetlands †, ha	0.55	0.64	0.46
Maximum difference in elevation between the wetland bottom and upland (palmetto line) , cm	42	39	33
Number of shallow wells used for weekly data collection	27	31	17
Number of water table recorders used for continuous data collection	3	2	1
Elevation at the pond recorder (m)	29.468	29.61	28.124
Elevation of the palmetto line ‡ (m)	29.89	30	28.449
Elevation at the upland recorder (m)	30.2	29.718	28.932

† Measured along the palmetto line; ‡ the elevation at the margin recorder = 30.108 m.

poorly drained. The soil type was primarily a typical Spodosol (Pomona fine sand, Utic Haplaquods; sandy, siliceous, thermic).

Within this site, three representative cypress wetland/pine systems, namely C, K, and N, were extensively instrumented (Table 3.1). This work reports the detailed studies of the three systems since most of the process-related data were collected and analyzed from these by the author. Data from Bradford Forest site were collected by Korhnak and Riekerk (Personal communication), and used mainly for model calibration and verification.

Bradford Forest (BF) Site

This site was located 9 km west of Starke, and 50 km northeast of Gainesville, in Bradford County (Figure 3.1). The climate, landscape, and vegetation were very similar to

that of the GNF site, but the 0-4 m thick clay aquitard below the surficial water table aquifer was more leaky as suggested by Pratt (1978).

In 1978, three watersheds (WS1, WS2, and WS3) designed to evaluate the effects of different treatments of low disturbance, high disturbance and control were created artificially by enhancing the pre-existing drainage divides with perimeter roads and ditches (Figure. 3.5). Treatment experiments were started in April 1979. Each watershed contained one water level recorder in the main cypress pond and one in the upland. All shallow wells and deep wells were monitored only during the first year of the project, but selected wells were monitored continuously. Runoff from each watershed was measured by a long-throated recording flume. Air temperature and rainfall data were collected from a central weather station and network of seven rain gauges (Riekerk, 1989). Brief information about the control watershed (WS3) has been described in Table 3.2.

Table 3.2. Site characteristics and instrumentation at the Control watershed (WS3), Bradford Forest[†].

Total surface area, ha	140
Surface area of cypress wetlands[‡], ha	66
Maximum difference in elevation between the wetland bottom and the upland, cm	50
Number of shallow wells (1m deep)	16
Number of deep wells (7 m deep)	9

[†] Information based on watershed conditions in 1978.
[‡] Measured along the palmetto line.

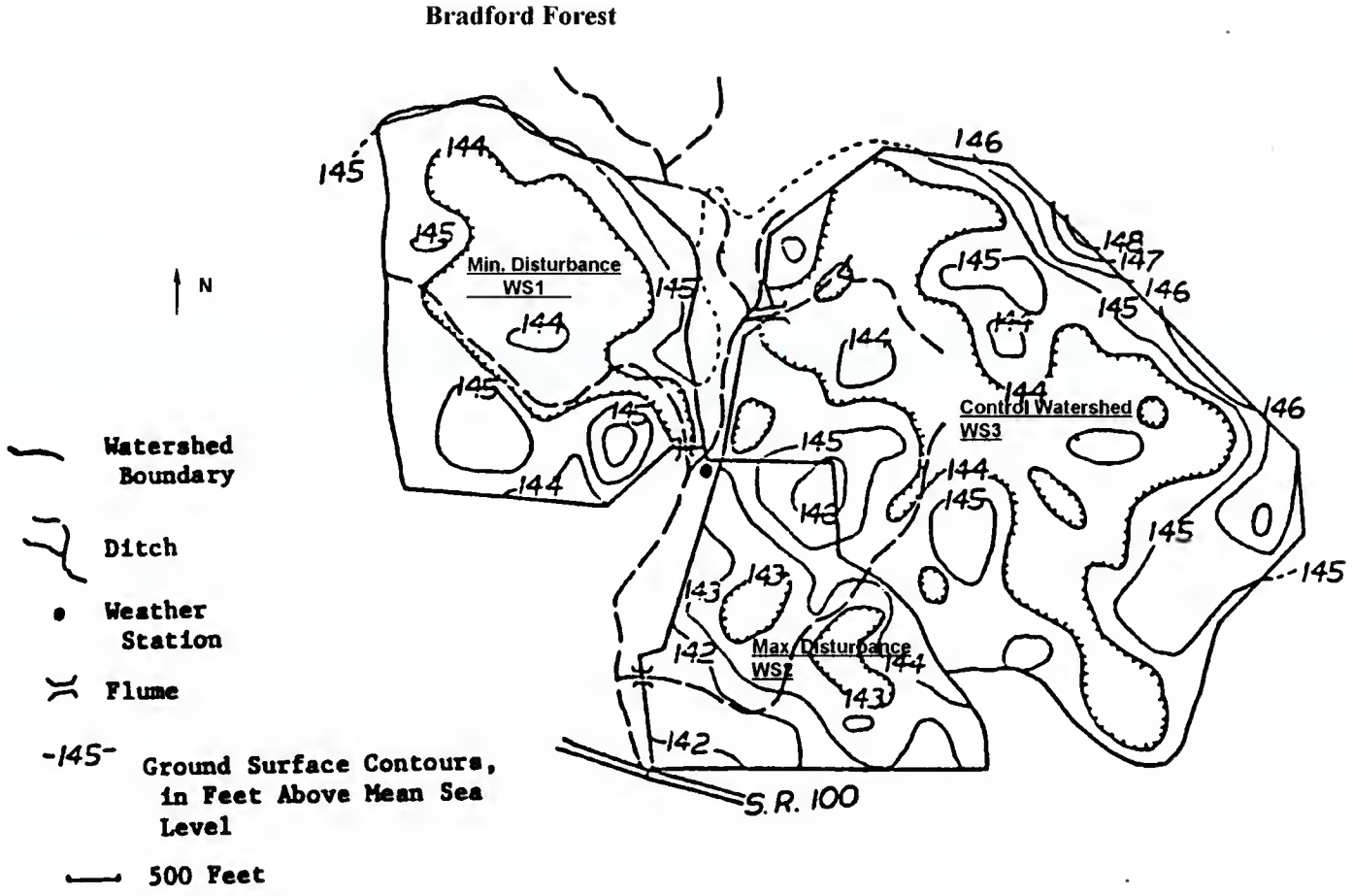


Figure 3.5. Topographic map and experimental design at the Bradford Forest site in Bradford County, Florida.

Methods for Field Data Acquisition and Analyses

As stated earlier, this dissertation only includes field data from the GNF site, and the following discussion is specifically for this site. The guide for investigations of different hydrologic components was the water balance, but focused on wetland-upland interactions for the present study (Figure 3.6).

The water balance of a watershed can be expressed as Equation 3.1 for any time scale from an hour to a year:

$$\Delta V = P_n \times A + S_i + G_i - ET \times A - S_o - G_o - D_s \quad (3.1)$$

and,

$$\Delta V = \Delta(V_p + V_s + V_u) = \Delta(f_1(wl) + f_2 (wl) + f_3(wl, \theta)) \quad (3.2)$$

ΔV = change in water storage (L^3);

P_n = net precipitation = precipitation (P) - interception by vegetation (P_i) (L);

A = surface area of the target system (L^2);

S_i = surface inflow across the system boundaries (L^3);

G_i = ground water inflow or subsurface inflow across watershed boundaries (L^3) ;

ET = evapotranspiration including soil and pond surface evaporation and transpiration from vegetation (L);

S_o = surface outflow across watershed boundaries (L^3);

G_o = lateral ground water outflow or subsurface outflow across watershed boundaries (L^3);

D_s = vertical deep seepage from water table aquifer across the watershed bottom (L^3);

V_p = volume of water in pond (L^3);

V_s = volume of water in saturated soil (L^3);

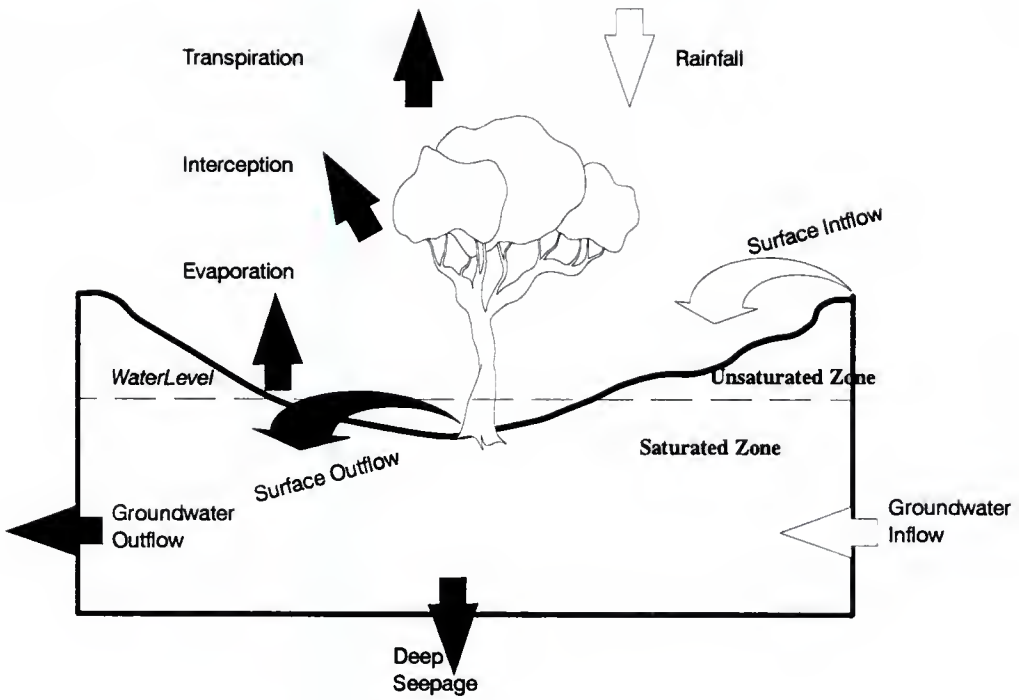


Figure 3.6. Hydrologic components in a wetland-upland system.

V_u = volume of water in unsaturated soil (L^3);

wl = water table level in the system (L);

θ = soil moisture content in the unsaturated zone;

f1, f2 and f3 are functions of water level or soil moisture content (θ) in the unsaturated zone.

This equation may be used in any system as long as the boundary conditions are determined. For a flatwoods system, surface flow and groundwater flow between wetland and surrounding upland represent one way of the energy and matter interactions of these two ecosystems. The change of surface water area in wetlands during a storm event or from season to season reflects the variable source of storm water runoff.

Data Acquisition

Net precipitation (P_n)

A standard weather station was established near the K pond, and hourly rainfall, average air temperature, humidity, and solar radiation data were recorded by a data logger. One standard rain gauge was placed in an open area adjacent to and one gauge inside of each pond to manually collect weekly rainfall and throughfall. Ten 10 cm wide and 75 cm long throughfall troughs made from polyvinyl chloride half-pipes were installed in each wetland and upland plot to determine rainfall interception by forest canopies. Six additional troughs were placed under the palmetto layer to account for understory interception. Throughfall data were collected from April 1993 to May 1994.

Soil moisture content (θ)

The hydrologic heterogeneity of flatwoods was reflected by spatial soil moisture

distribution as well as by groundwater table depth. Soil moisture content was measured using Time Domain Reflectometry (TDR) method (Topp, 1980; Ledieu et al., 1986) during June 1993 - December 1993 on a weekly basis. The objective of these measurements was to establish a relationship between water table depth and volumetric water content of the unsaturated zone for both uplands and wetlands. This relationship will be used to determine initial soil moisture conditions for the simulation model, and for ET estimation by the water balance method.

Two transects were established from the wetland into the upland with measurement spots at 25-m intervals. At each spot, paired steel rods were pushed laterally into a vertical soil pit wall as sensors for direct measurement of volumetric soil water content by the TDR method (Figure 3.7). The number and layering of rods depended on the clay depth and water table conditions of the particular sites. During the excavation of the pits that were 0.5 m wide and 1 m deep, intact soil samples for each layer were collected with copper rings 5 cm in diameter and 4 cm in height for analysis of soil physical properties.

The equation for the calculation of volumetric soil moisture content from TDR readings was adopted from Topp (1980):

$$\theta = -0.053 + 0.0292 \times K - 0.00055 \times K^2 + 0.0000043 \times K^3 \quad (3.3)$$

where, K is the reading from the TDR equipment.

Calibration of the above equation was made by a gravimetric soil moisture sampling method (Figure 3.8). Considering the sampling errors in determining soil bulk density to convert gravimetric to volumetric soil moisture content, and the variability between sampling points, the validity of the general equation with $R^2 = 0.76$ appeared to be justified.

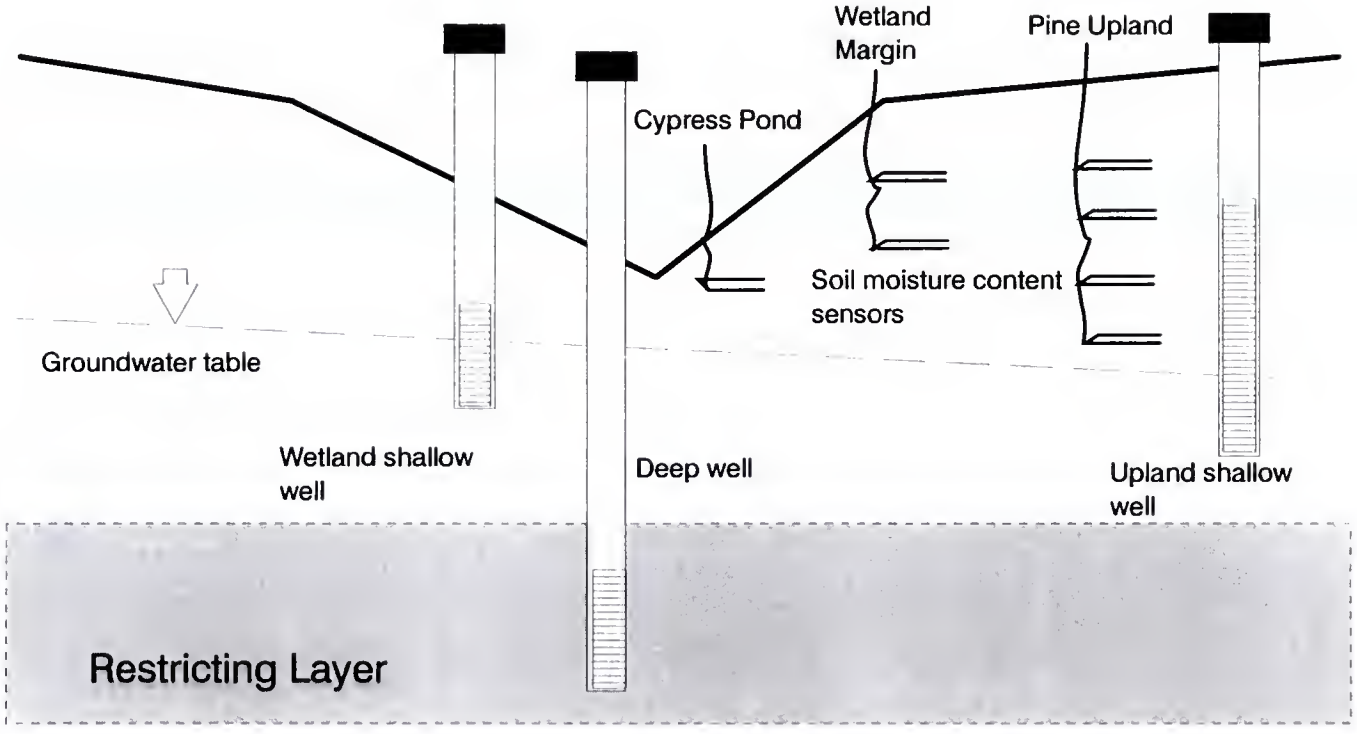


Figure 3.7. A vertical view of instrumentation at the C wetland/upland showing transects for soil moisture measurement, shallow water table wells and a deep well.

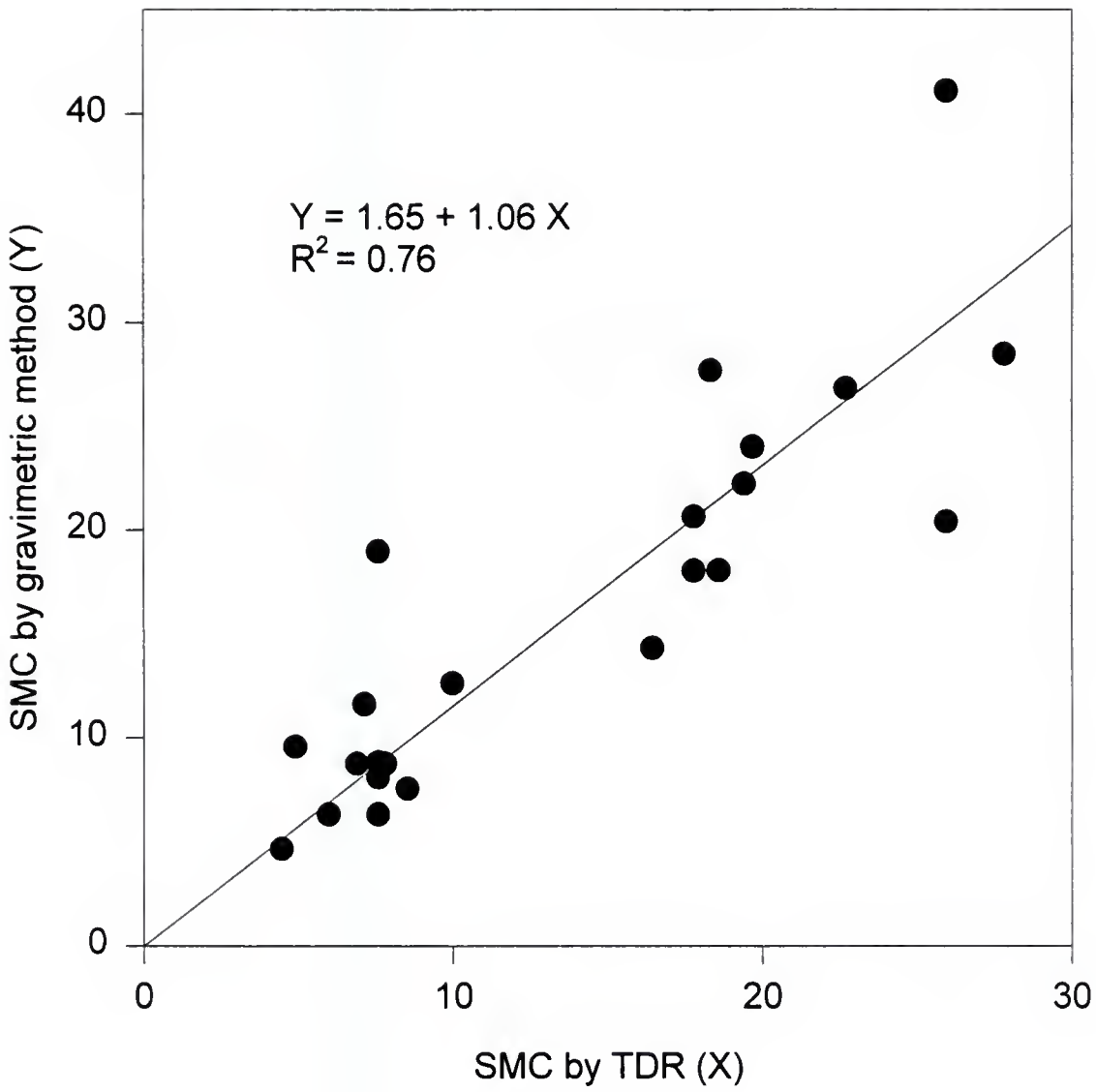


Figure 3.8. The calibration curve for soil moisture content (SMC) measurements with the TDR method.

A water table well was installed down to the clay horizon nearby each spot for soil moisture content measurement to measure the water table level during each visit.

Groundwater flow (G_i/G_o)

More than 20 shallow groundwater wells were installed for each of the three selected wetland-upland systems to determine groundwater flow gradients. The water table map for each measurement, was constructed with a 10-cm contour interval. The 5 cm diameter and 1.5 m long polyvinyl chloride (PVC) wells were installed in holes made with a 5-cm diameter hand auger. The lower 1 m of the pipe had well-screening and was closed at the bottom. In most cases, a clay layer was encountered about 1.5 m below the ground surface. In each wetland, a 8-cm diameter hole was dug with a power auger and a 5-cm well with a 1-m long screen installed at 7 m depth to determine deep seepage from the perched water table to the secondary aquifer as sketched in Figure 3.7. Soil samples obtained during the drilling process were brought to the laboratory for examination and re-construction of the geologic profile. Four to six 50-m transects with 3 wells at 25-m intervals radiating from the wetland edge to the upland were established for each system (Figures 3.9, 3.10, and 3.11). The water level near the center of each wetland was recorded continuously with a 15-minute punch tape recorder. The groundwater table changes in an adjacent upland well about 50 m from the wetland margin was recorded on weekly charts with a Stevens Type F recorder. Water table data were collected since January 1992 for the K and N wetlands, and March 1993 for the C wetland. Groundwater tables in the three upland sites have been recorded continuously since April 1993.

A boundary must be first established to calculate groundwater flow in or out of a

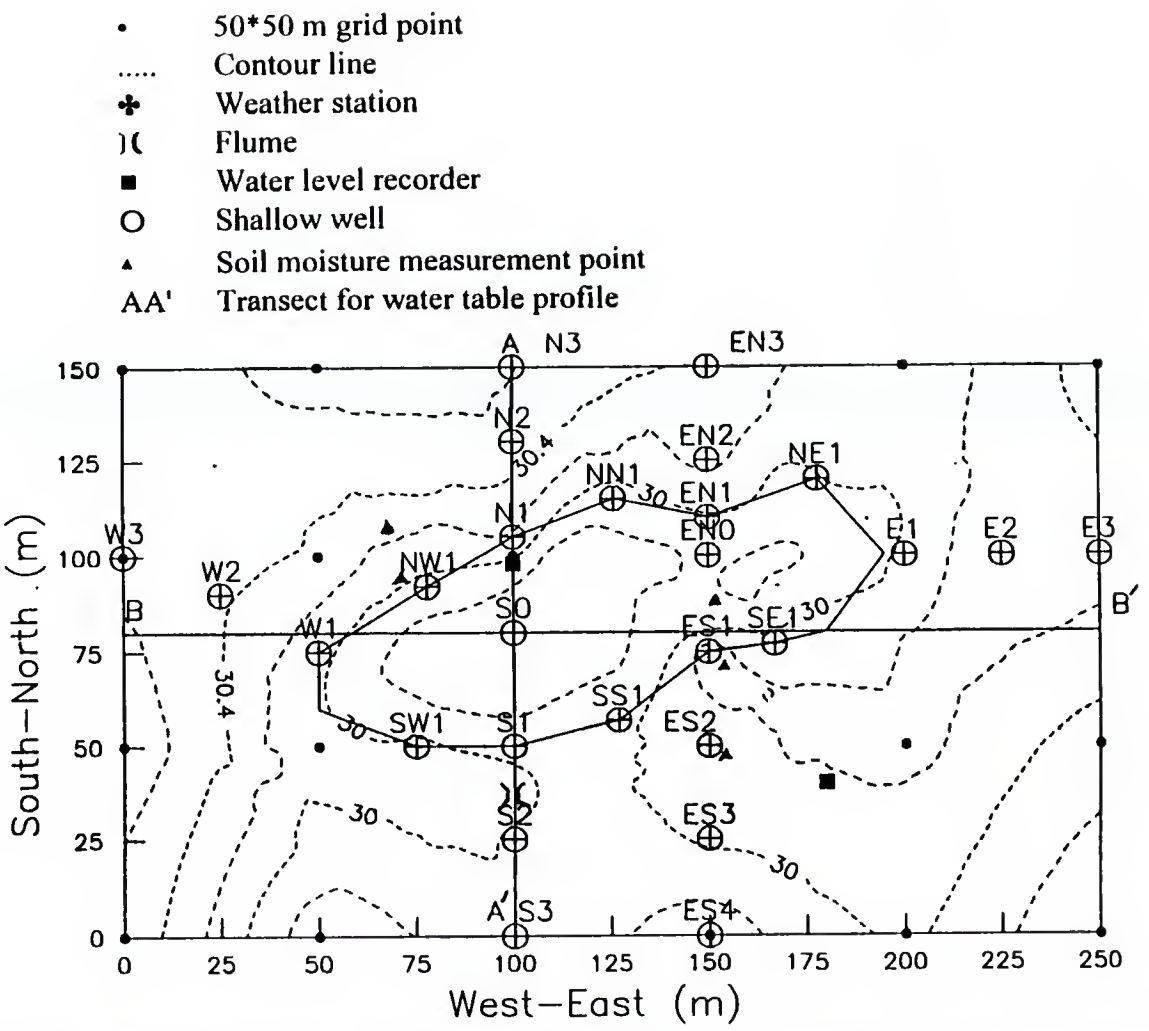


Figure 3.9. Instrumentation in the C wetland in transects of shallow wells radiating from the wetland, wetland margin, to the surrounding upland.

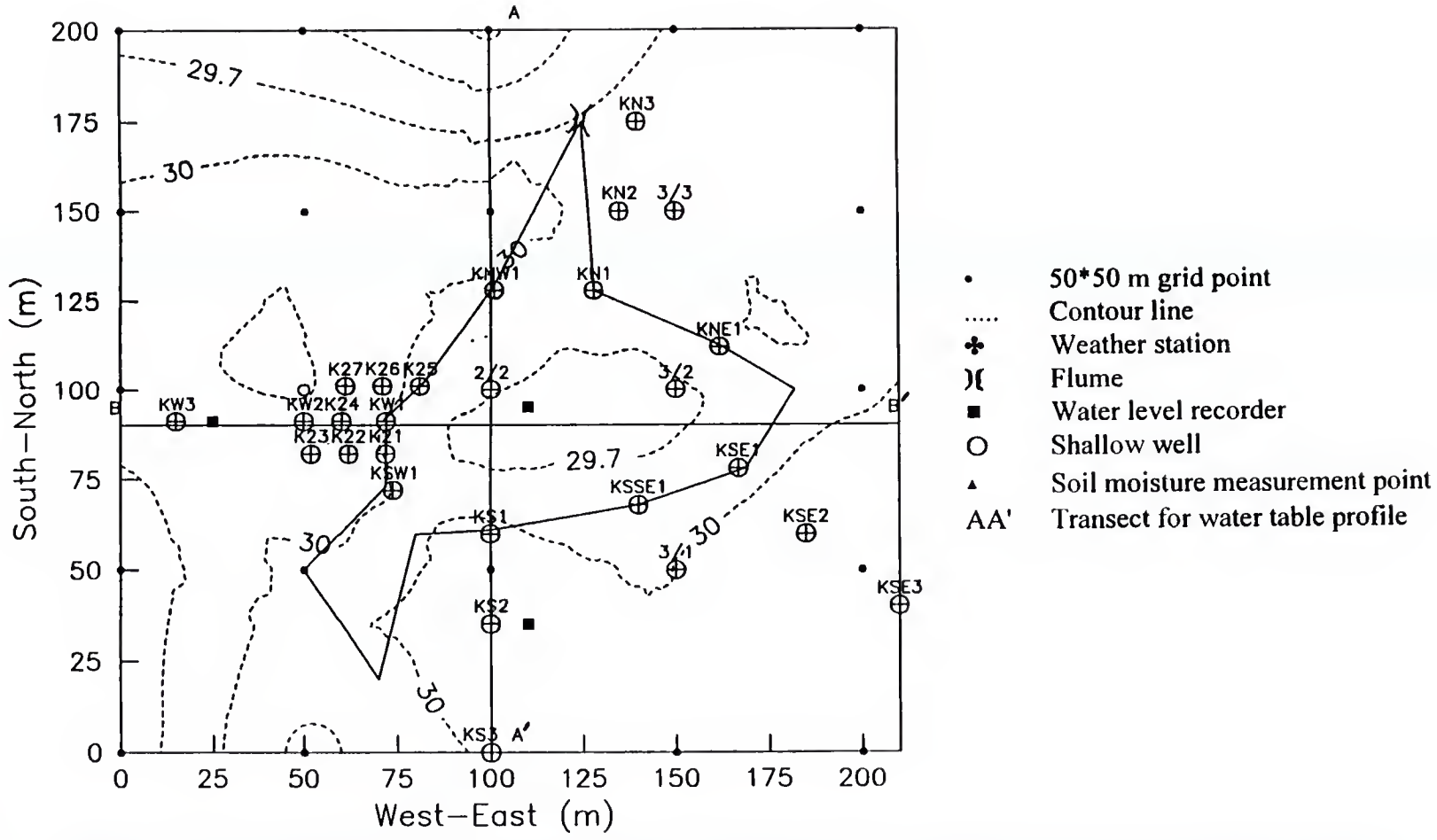


Figure 3.10. Instrumentation in the K wetland in transects of shallow wells radiating fromthe wetland, wetland margin, to the surrounding upland.

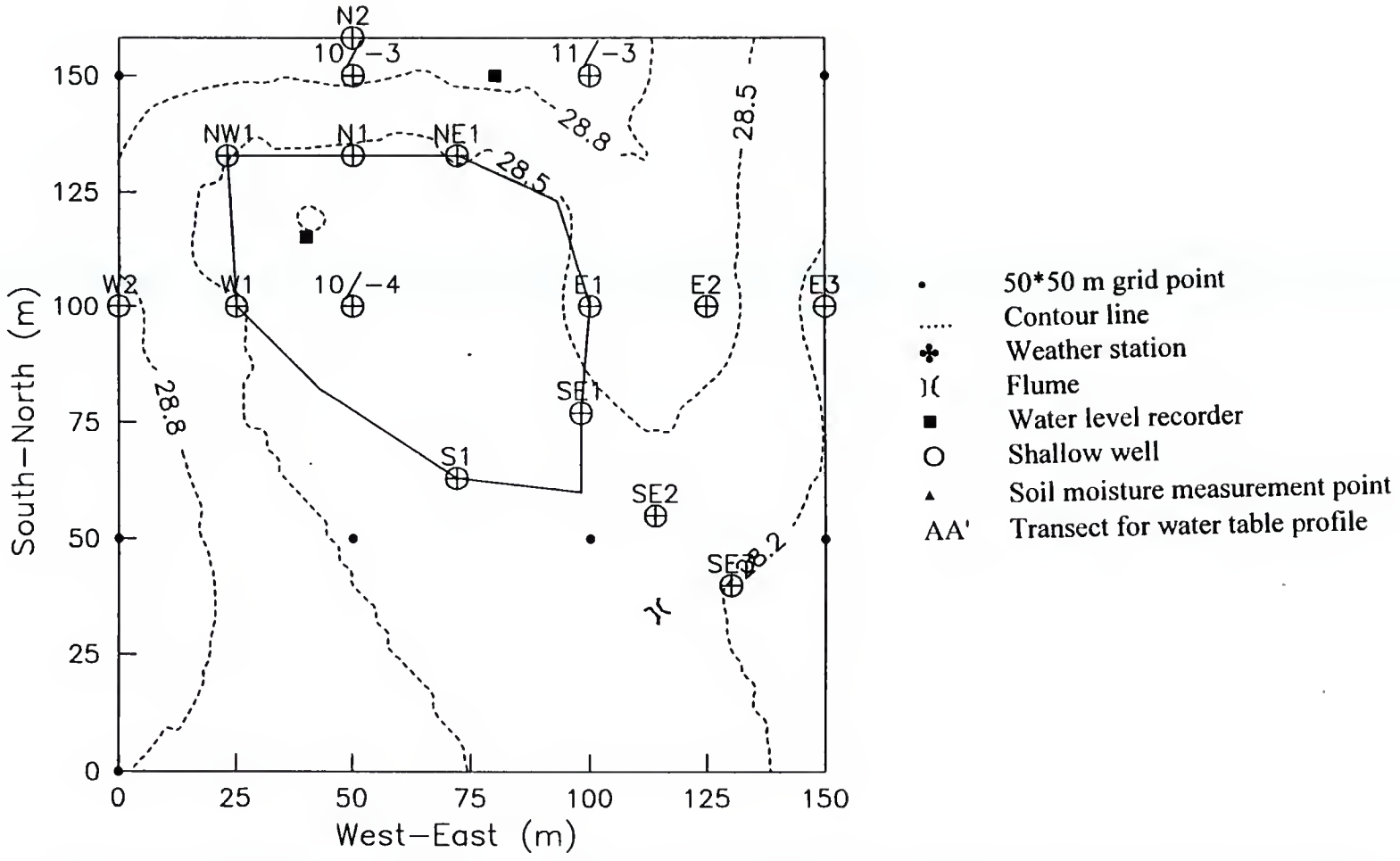


Figure 3.11. Instrumentation in the N wetland in transects of shallow wells radiating fromthe wetland, wetland margin, to the surrounding upland.

system. Since the water table in wetlands varied dramatically during the year, the boundary for groundwater flow calculations as well as water balance was delineated by the minimum polygon which can cover the wetland surface area during the wettest season.

The method to calculate groundwater flow quantity was based on Darcy's equation (Fetter, 1988):

$$g_i = K_s \times A_i \times I_i \qquad (3.4)$$

$$G = \sum_{i=1}^{N} g_i T \qquad (3.5)$$

where,

g_i = groundwater flow recharge/discharge through the vertical wetland boundary segment i (m^3/day);

K_s = hydraulic conductivity of the water table aquifer (m/day);

A_i = the i^{th} cross-sectional area of groundwater flow (m^2), product of the length of a segment of the boundary line (m) and the aquifer thickness (m);

I_i = hydraulic gradient (m/m) at a right angle across the boundary segment, positive from the upland to the wetland;

T = time interval for the calculation (day);

G = total groundwater flow amount into area of a wetland during the time period of T days (m^3).

The boundary line was divided into eight segments (N = 8) with fixed length and the net groundwater flow amount was the sum of all the positive and negative flows across all

the segments. Normally, four measurement periods were used for calculation of monthly averages.

A finite element analysis method was employed to further explore the dynamics of water flow direction and velocity at certain particular points of interest (Keen, 1992). In the finite element theory (Segerlind, 1976, 1984), the hydraulic gradient of a two dimensional domain can be expressed as:

$$\begin{bmatrix} \frac{\partial h}{\partial x} \\ \frac{\partial h}{\partial y} \end{bmatrix} = \frac{1}{2A} \begin{bmatrix} b_i & b_j & b_k \\ c_i & c_j & c_k \end{bmatrix} \begin{bmatrix} h_i \\ h_j \\ h_k \end{bmatrix} \qquad (3.6)$$

where, the determinant 2A is defined as:

$$2A = \begin{vmatrix} 1 & X_i & Y_i \\ 1 & X_j & Y_j \\ 1 & X_k & Y_k \end{vmatrix}$$

and X and Y are the coordinates of any three points i, j, and k of a triangular element. For the study of groundwater flow, these three points may represent well locations. The coefficients a, b , c are calculated from the X and Y values.

$b_i = Y_j - Y_k$

$c_i = X_k - X_j$

$b_j = Y_k - Y_i$

$c_j = X_i - X_k$

$b_k = Y_i - Y_j$

$c_k = X_j - X_i$

Writing the differential gradient matrix with two discrete equations, the flow direction and hydraulic gradient (I_f) (m/m) can be evaluated by:

$$I_f = \sqrt{(\frac{\Delta h}{\Delta x})^2 + (\frac{\Delta h}{\Delta y})^2} \qquad (3.7)$$

The average linear velocity with which water actually moves through pore spaces was defined as (Fetter, 1988):

$$V_w = -\frac{K_s\ dh}{n_e\ dl} \qquad (3.8)$$

where,

V_w = groundwater velocity (cm/day);

n_e = effective porosity;

K_s = saturated hydraulic conductivity (cm/day);

I_f = dh/dl = hydraulic gradient (water table gradient) (m/m).

The flow direction α (0-360 degrees counter clockwise) was defined by the three well locations, i, j, and k. It was expressed as:

$$\alpha = \arctan [\ (\Delta h/\Delta y)/(\Delta h/\Delta x)\ ] \qquad (3.9)$$

This finite element method provided a convenient way to study the variability of water flow properties over a continuous time period if three water table recorders were used, as was the case for the K wetland, or for different seasons for those locations where water table data were collected on a weekly basis.

Computer softwares (SURFER, 1989) were used to interpolate measured groundwater table data from shallow water table wells to study the spatial distribution of the

water table across the wetland-upland systems.

The saturated hydraulic conductivity (K_s) was determined in situ by the Bouwer and Rice method (Bouwer and Rice, 1976; Rice, 1989). Although this method may have a 10% - 25% measurement error, its accuracy has been justified as being acceptable and has been widely used in estimating K_s for unconfined aquifers (Brown and Narasimhan, 1995). The expression of K_s was derived as:

$$K_s = \frac{r_c^2 \, Ln(R_e/r_w)}{2 \, L} \, \frac{1}{t} \, \ln(\frac{y_0}{y_t}) \qquad (3.10)$$

where,

K_s = saturated hydraulic conductivity (LT^{-1});

r_c = inside radius of the well (L);

L = the length of well perforation (L);

R_e = the effective radius over which y is dissipated (L);

r_w = well radius (L);

y_t = the vertical distance between the water level in the well and the equilibrium water table in aquifer (L);

$y_0 = y(t_o)$= initial maximum head change (L);

$y_t = y(t)$ = the head change at time t after the weight was removed from the well (L).

The formula to determine ln (R_e/r_w) for a fully penetrating well, which is the case of our experiment, was given as:

$$Ln\ (R_e/r_w) = [\frac{1.1}{\ln(H/r_w)} + \frac{C}{L/r_w}]^{-1} \qquad (3.11)$$

where, H = L, and the constant C can be found in Bouwer and Rice (1976).

Field measurements of K_s for each existing shallow well were conducted during the winter of 1994 when the groundwater table elevations were relatively high. A pressure transducer and displacement weight were placed in the well under the water table (Figure 3.12). After re-equilibrium of the water table, the weight was pulled out to create an instantaneous change of gradient that was recorded at a 5-second interval. This data set was used to calculate saturated conductivity of the soil in the water table aquifer. An example of the calculation of K_s is presented in Figure 3.12.

Surface flow (S_i/S_o)

Topographical gradients are slight in natural flatwoods and soils have high infiltration capacities, both of which promote infiltration. However, shallow sheet flows occur after storms during the wet season when the water table reaches the ground surface. The sheet flow meanders through cypress ponds in a diffused fashion toward the streams. This means that the surface flow farther away from the streams in flatwoods could be ephemeral. As a result, field measurements of surface flow in flatwoods is extremely difficult. Ditching between wetlands and roading around wetlands may alter the topography to facilitate surface runoff and better define watershed boundaries.

A V-shaped recording flume was installed to quantify the surface outflow at the apparent outlet of each wetland system. Installation of flumes at the inlets of K and N

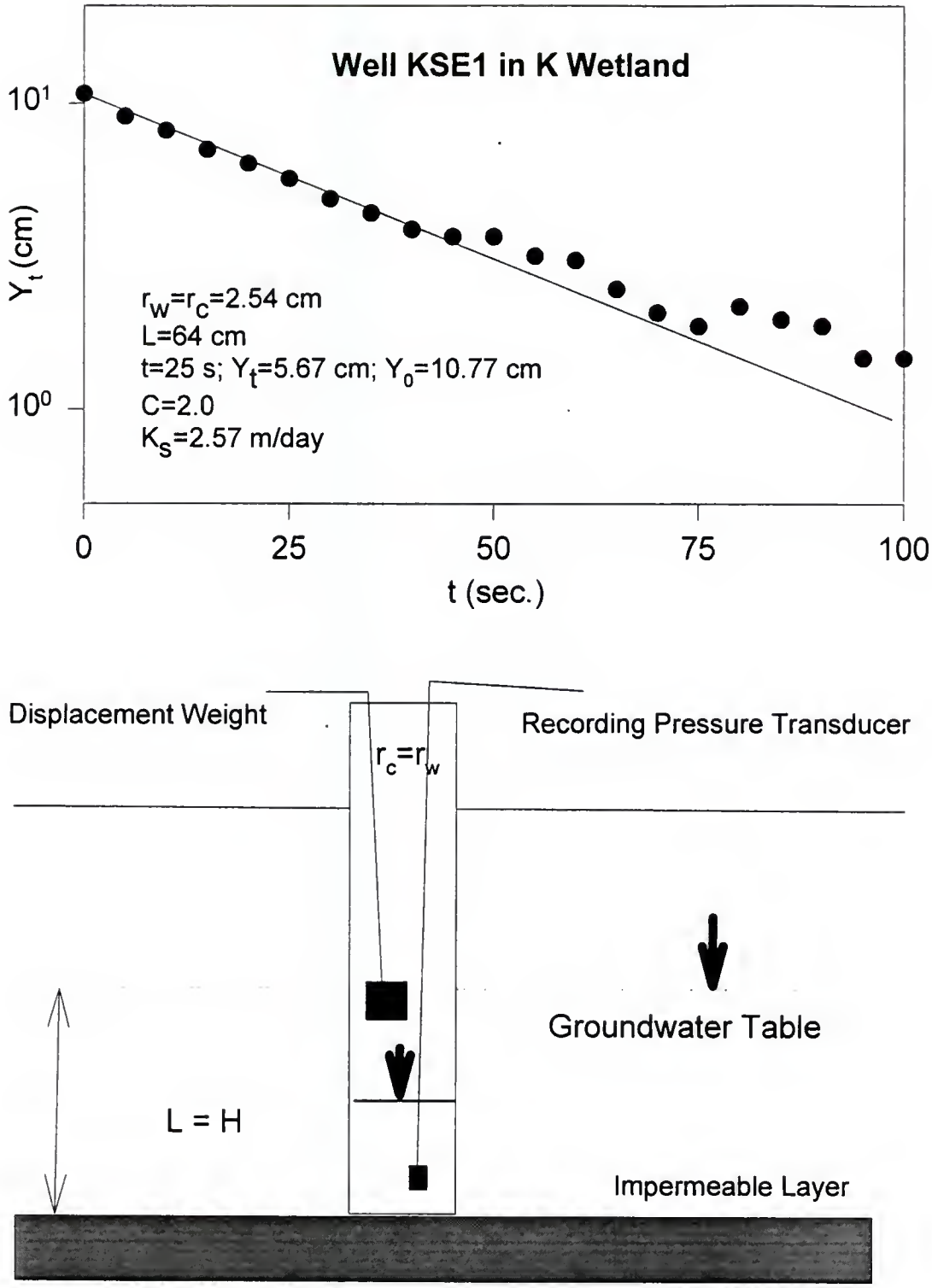


Figure 3.12. An example of the calculation of the saturated hydraulic conductivity (K_s) determined by the Bouwer and Rice method.

wetlands was useless because of the very low gradient. Instead, a smooth PVC culvert with a 28-cm diameter was used in combination with two water table level recorders for each inlet. Flow velocity through these pipes was measured with a low-velocity flow meter to calibrate the stage-discharge relationship. Both the N and K wetlands had inflow and outflow during the wet season while the control C wetland only had outflow during extreme wet periods and no significant surface inflow has been observed. To concentrate surface flow pathways and avoid bypassing the flumes, 30-cm high sheet metal boundary wings were buried 10 cm into the ground surface adjoining the inlet and outlet recorders.

Eight-hour intervals were used to calculate daily total flow volume from the stage hydrograhs. The equation for calculating surface outflow rate in the flumes was :

$$Q = 0.001428\ H^{2.7087} \qquad (3.12)$$

where,

Q = flow rate (m^3/s); and,

H = stage height of surface water level in the flume (m).

Deep seepage (D_s)

Deep seepage represents vertical water loss/gain through the bottom boundary from the water table aquifer to deeper aquifers. A deep well about 7 m long as sketched in Figure 3.4 was installed in each wetland to estimate the magnitude of possible deep seepage by comparing the pond water level to that in the deep well.

The vertical seepage rate was calculated by Darcy's equation:

$$q_v = -K_v \frac{H_l - H_s}{L} \times 1000 \qquad (3.13)$$

where,

q_v = vertical seepage rate (mm/day);

K_v = restrictive layer's vertical hydraulic conductivity (m/day);

H_s = hydraulic head at the top of the restrictive layer (m);

H_l = hydraulic head at the bottom of the restrictive layer (m);

L = the thickness of the restrictive layer (m).

Change in storage (ΔV)

As shown in the water balance equation, the water storage component includes surface water in the pond (V_p), and soil water in both the saturated (V_s) and the unsaturated zones (V_u). The change in water storage was evaluated on a monthly basis by calculating the three components separately. A 10 m by 10 m grid system was established in each pond and water table depths were measured at each intersection at a time when the water table was high. The bathygraphy of each wetland-upland system was determined by the computer software SURFER (1989) from this water table depth data and associated grid point elevations. The relationships between pond water volume (V_p) or pond water surface area (A_p), and water level (wl) were estimated with this information (Figures 3.13, 3.14, 3.15). The water storage in the unsaturated zone (V_u) was calculated assuming that the soil water content was a function of water table level, although the water content in wetland soils did not change significantly. The water storage in the saturated zone (V_s) was the product of the thickness of the saturated zone and its porosity (ρ).

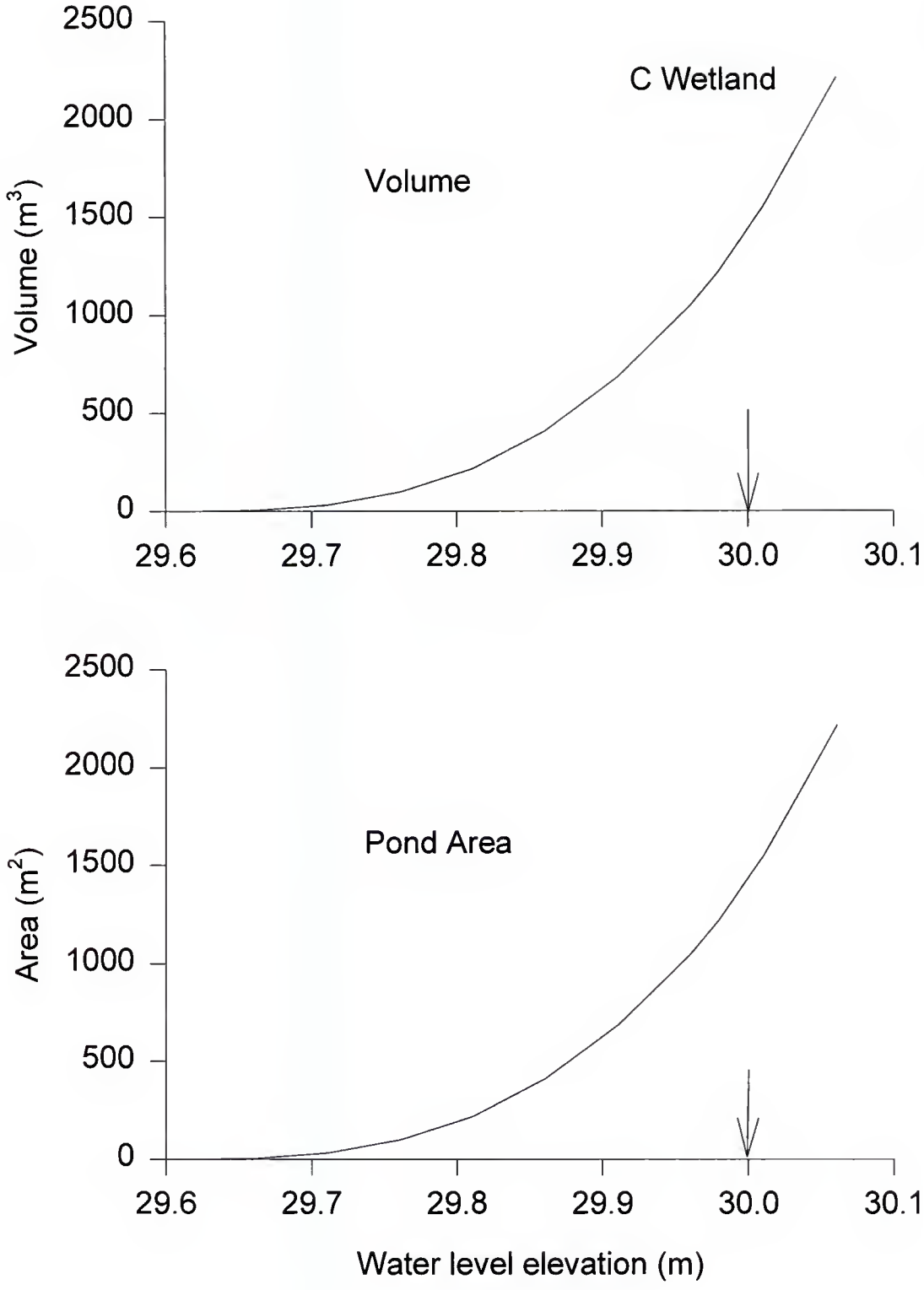


Figure 3.13. Relations between water level elevation, and pond surface area and water volume for the C wetland. The palmetto line is indicated by the arrow.

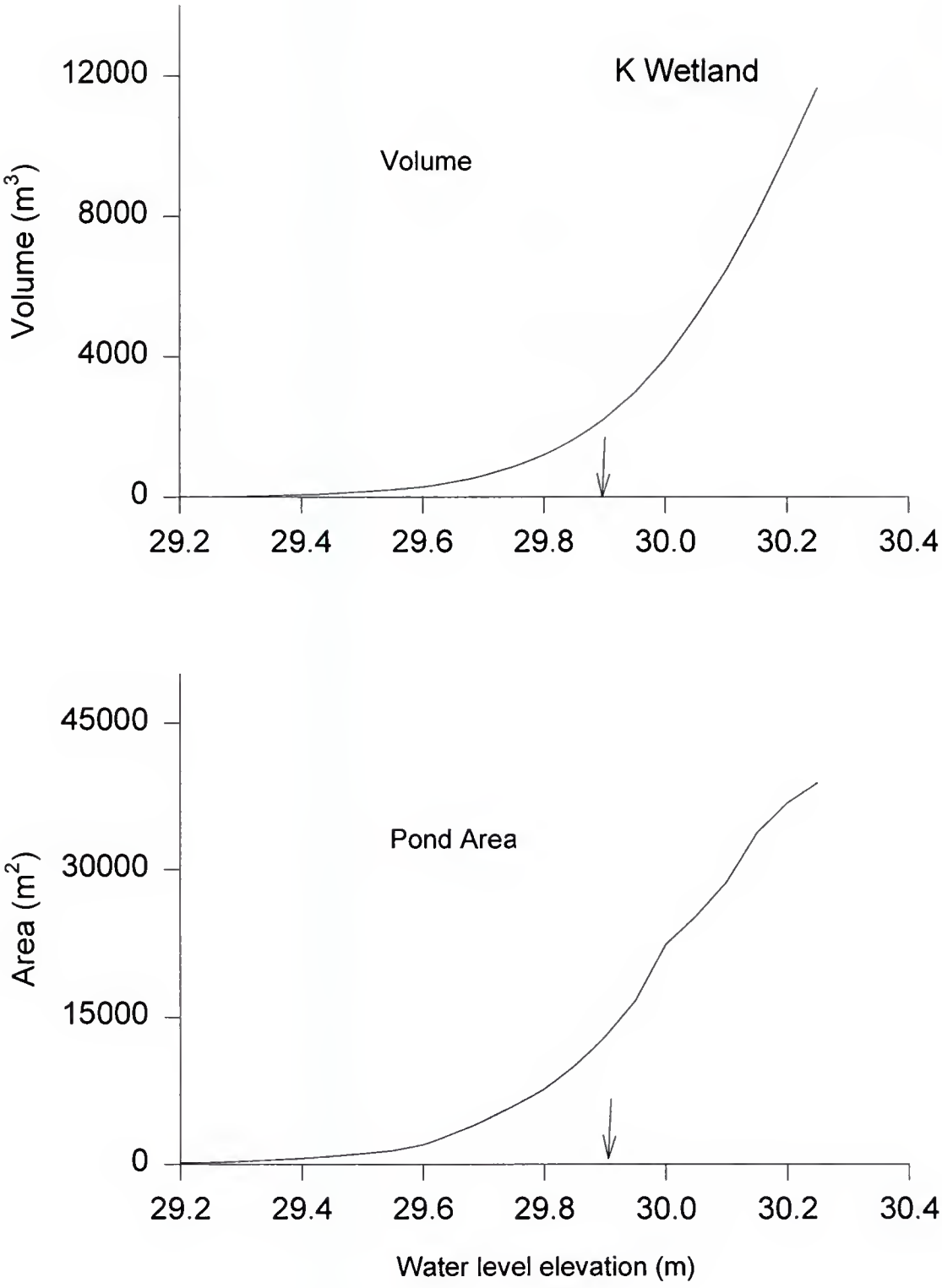


Figure 3.14. Relations between water level elevation, and pond surface area and water volume for the K wetland. The palmetto line is indicated by the arrow.

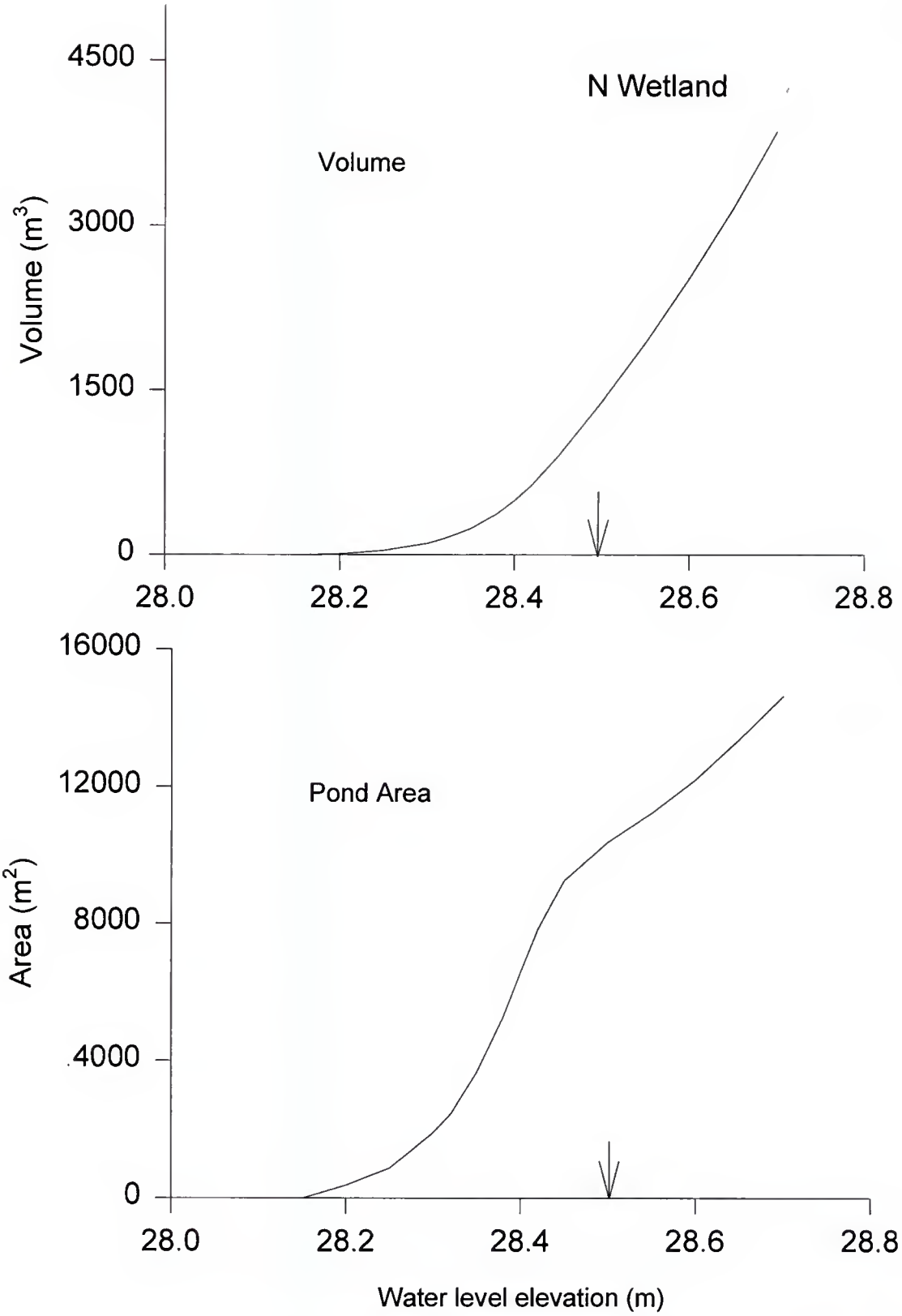


Figure 3.15. Relations between water level elevation, and pond surface area and water volume for the N wetland. The palmetto line is indicated by the arrow.

Evapotranspiration (ET)

There are four categories for ET measurement, namely, the water balance category, the meteorological category, the physiological category, and the empirical equation category. The water balance category may be represented by the soil moisture method in the unsaturated root zone (Kirsch, 1993) or saturated zone (White, 1932; Freeze and Cherry, 1979; Gerla, 1992), the lysimetry method (Patric, 1961; Fritschen et al., 1977; Dunin et al., 1985; Riekerk, 1985), and the watershed method, depending on the scale of interest. Meteorological methods are designed to quantify the change of water from liquid to vapor and vapor movement in the lower atmosphere, and to combine these processes with the energy budget of the system. These methods are represented by aerodynamic method, eddy correlation and Bowen ratio energy balance method (Fritschen and Simpson, 1985). Physiological methods have been used in the study of water vapor loss (transpiration) along with photosynthesis and other plant physiological processes and are represented by porometer, chamber and sap-flow methods. Empirical equation methods include the Penman and Thornthwaite equations with a crop coefficient, Class A pan evaporation corrected by a coefficient, and correlations among air temperature, solar radiation and ET (Jones et al., 1984). Although no one approach is appropriate to all situations, under certain conditions one may be more effective than others. For example, the watershed water balance method is fairly accurate if the watershed boundaries are well defined and impermeable, and other hydrologic components such as precipitation and runoff are available. The lysimetery method is more useful to study small scale systems with more detail and accuracy.

The water level in wetlands is sensitive to ET. Similarly, vertical percolation in

flatwoods uplands is limited by the underlaying clay layers and the resulting shallow ground water table in the rooting zone is very sensitive to ET. These conditions are favorable for estimating ET by examining the water level or water table hydrographs, which are the dynamic signatures of change in storage, resulting from change in the water balance. However, the following considerations may make this method less accurate or even unjustifiable for estimation of ET at high resolution (e. g. daily): (1) Lateral drainage or degassing processes may be significant but are difficult to quantify during storms or immediately after storm events; (2) Water content in the unsaturated zone decreases significantly when the water table is low; (3) Surface flow or near-surface quick flow occurs during wet seasons but is difficult to measure due to poorly defined boundaries; and (4) Uncertainty of groundwater loss by deep seepage (leakage). Nevertheless, the water balance method remains a useful and relatively low-cost method to study the importance of each hydrologic component in a complete water cycle in pine flatwoods.

In this study, monthly ET was estimated for both wetlands and uplands based on the water balance equation for the entire soil profile including the unsaturated soil zone, saturated soil zone and/or wetland surface water. Longer time intervals reduced errors caused by above considerations #1 and #2, and careful selection of the location of water table recorders reduced the problems in considerations #3 and #4, especially for the calculations for pine uplands.

CHAPTER 4
DATA RESULTS AND ANALYSES

The following data analyses were based on data collected since 1991, but complete data sets for the comparison of wetlands and uplands water balances were from April 1993 to May 1994.

Precipitation and Vegetation Interception

Weather Data

In Alachua County, rainfall is primarily generated by two mechanisms: (1) convective systems due to land surface heating combined with a double sea breeze convergence in summer months, and (2) frontal weather systems in the winter and spring months (Dohrenwend, 1978). Hurricane and tropical storms modified these annual rainfall patterns. An annual rainfall of 1330 mm with air temperature of 21°C was normal. During the three years of study, we had a wet year of 1992 and two somewhat dry years of 1993 and 1994 (Figure 4.1). The year of 1992 had an annual rainfall amount of 1553 mm and a lower average air temperature of 17 °C. The years of 1993 and 1994 had annual rainfall amounts of 1104 and 1240 mm, respectively, and a normal average annual air temperature of 20°C.

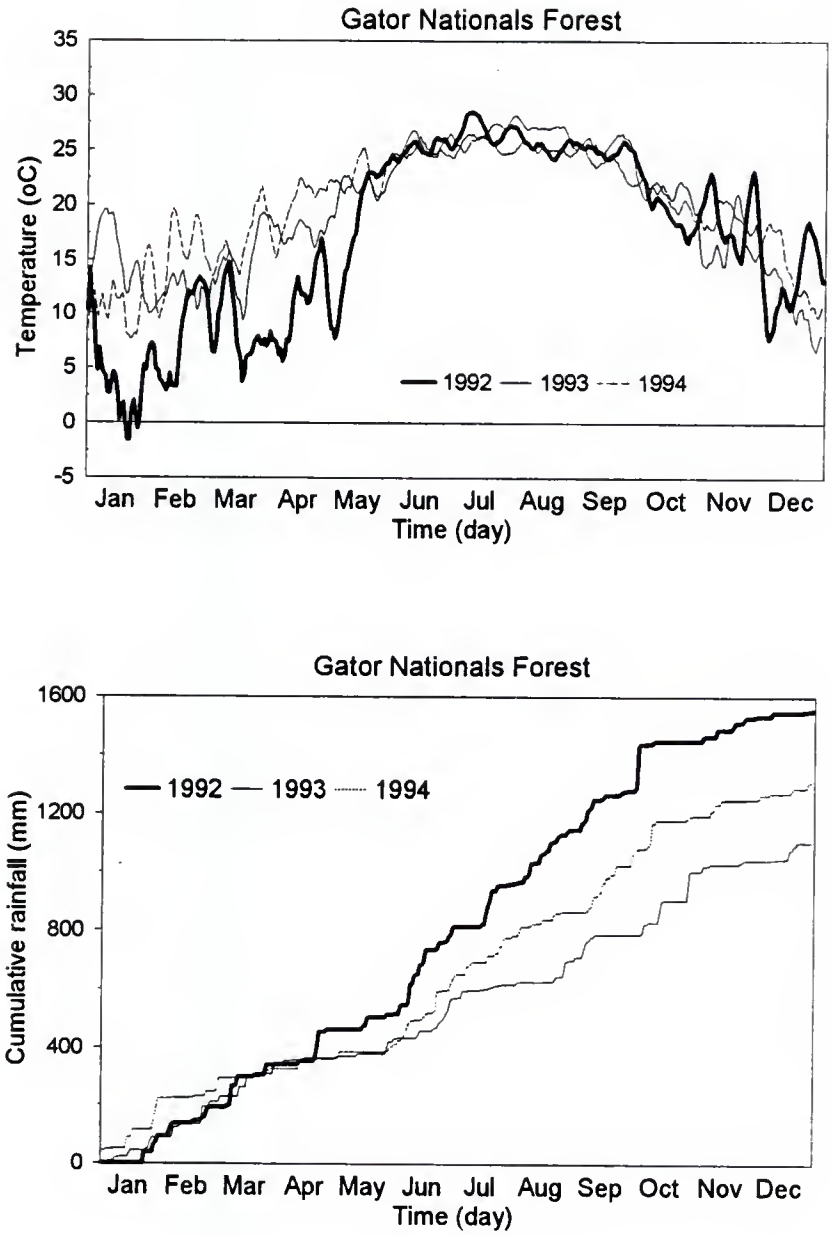


Figure 4.1. Weekly average air temperature and cumulative rainfall for 1992, 1993, and 1994 at the study site.

Vegetation Interception

Vegetation interception (P_i) represents that part of rainfall intercepted by vegetation surfaces that does not reach the soil surface during storm events, and eventually returns to the atmosphere by direct evaporation. Canopy interception has been documented as a significant component in the forest canopy energy balance, influencing plant transpiration, and water budgets of forest stands (McNaughton and Jarvis, 1983; Lankreijer et al., 1993). In this study, interception was calculated as the difference between rainfall and throughfall. Previous studies suggested that the stemflow component represented less than 2.5% and 1% of rainfall for cypress wetlands and pine uplands respectively (Heimburg, 1976; Gholz et al., unpublished data). Stemflow was not evaluated due to its insignificance, however, for the upland forests on our site with low tree density (500 trees/ha), stemflow may have been higher.

The canopy interception rate (IR) was defined as:

$$IR=\frac{P-P_t}{P}=1-\frac{P_t}{P} \qquad (4.1)$$

where, P is rainfall above forest canopies and P_t is throughfall (mm).

Weekly throughfall closely followed precipitation as shown in the regression equations for both uplands and wetlands of the three sites combined (Figure 4.2). However, the correlation between the interception rate and precipitation was poor for both uplands and wetlands as shown in Figure 4.3.

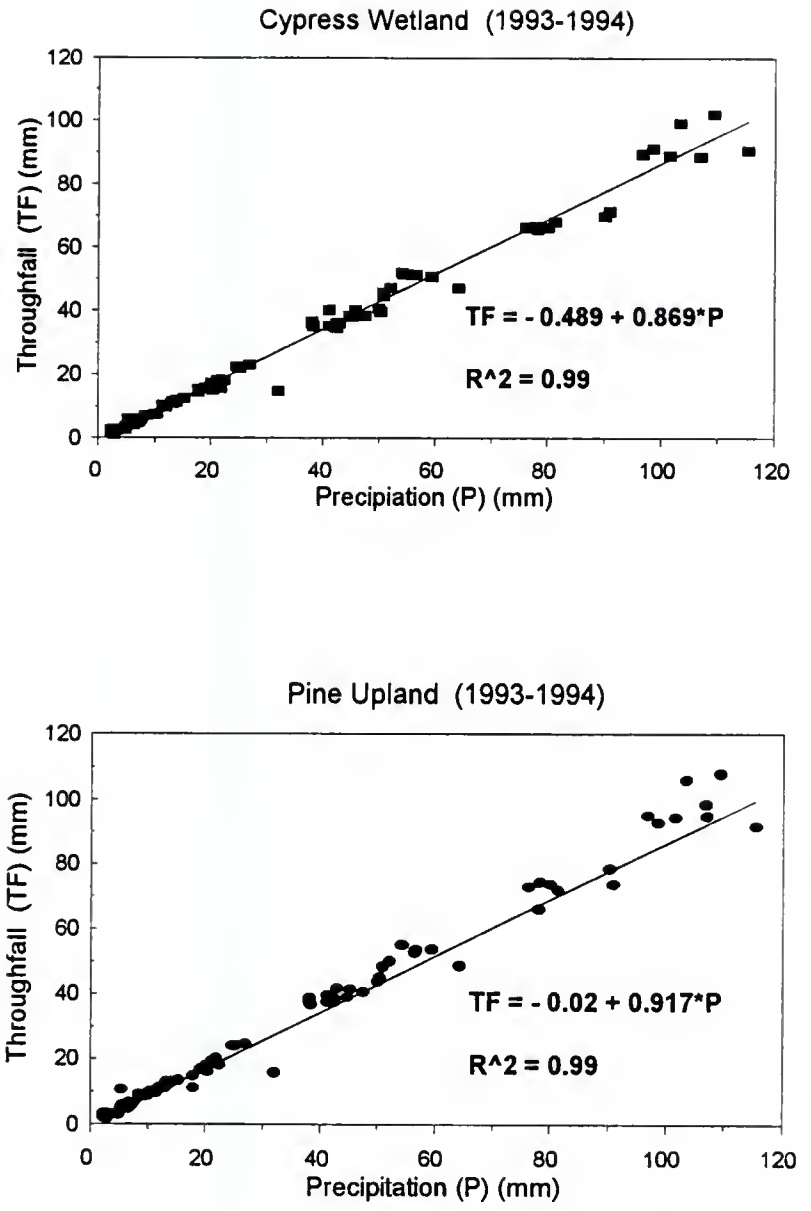


Figure 4.2. Relations between precipitation and throughfall for cypress wetlands and pine uplands.

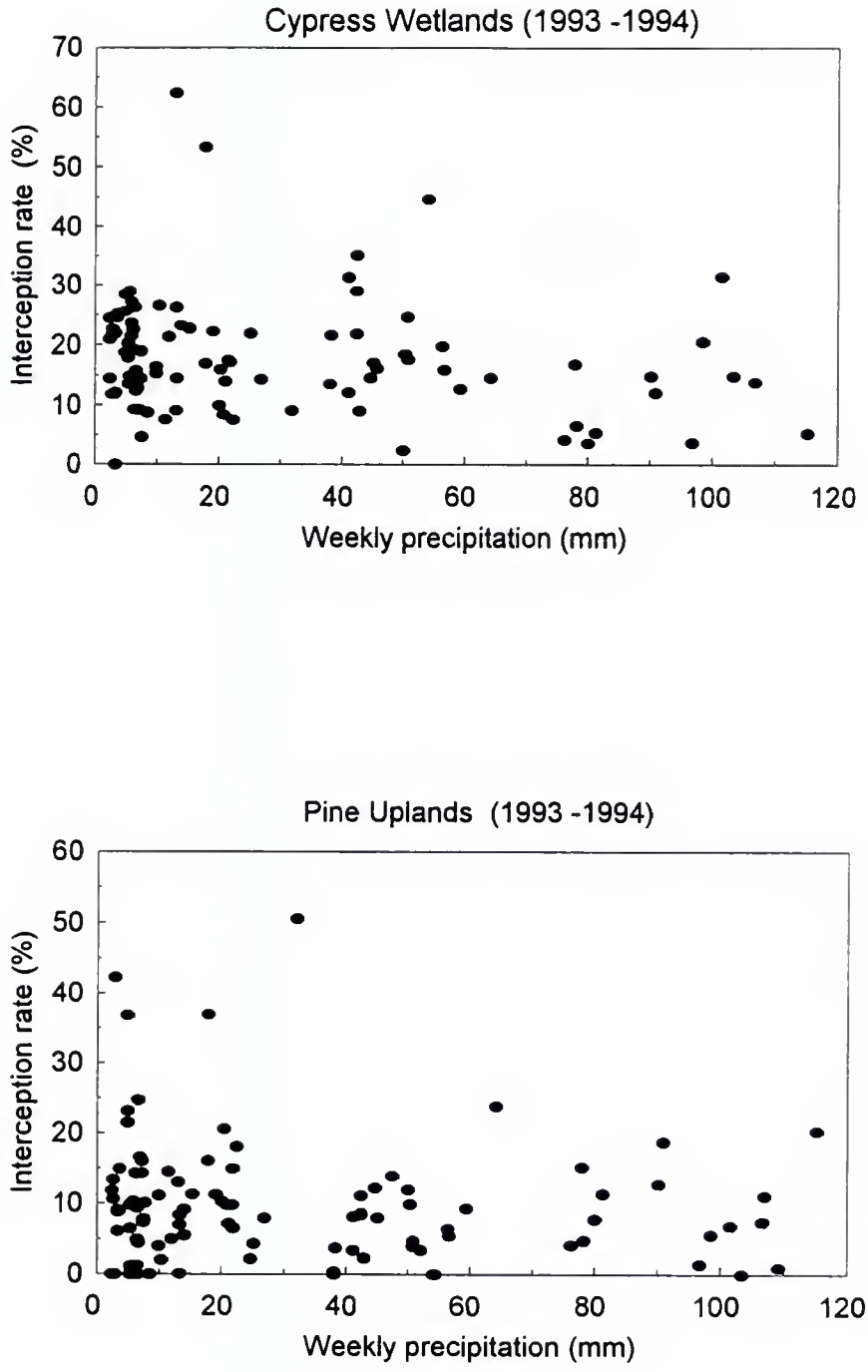


Figure 4.3. Relationships between canopy interception rates (Interception/Precipitation) and precipitation for cypress wetlands and pine uplands.

The high variability of IR for a certain forest stand may be due to many factors, such as storm size, rainfall intensity, wind speed, air temperature and leaf area index (LAI) during each measurement. For deciduous tree species, such as pond cypress, the leaf area is especially significant for canopy interception. The regression equations suggested that the maximum canopy storage was 0.56 mm and 0.02 mm for cypress wetlands and pine uplands (excluding shrubs), respectively. Gholz et al. (unpublished data) reported 0.77-mm of canopy water storage for mature slash pine stands with a tree density of 1190 $\pm$ 118 trees ha^{-1}, twice as high as in the present research study. Apparently, the low storage value of pine plantations on the project site reflected the low tree density and low LAI. The deciduous nature of cypress trees caused low canopy storage capacity in winter months from mid-November to end of March.

Figure 4.4 shows the seasonal distribution of the interception rate of weekly measurements during 1993-1994. The average interception rates were 16.9% (Standard Deviation, STD = 11.1%) and 9.3% (STD=10.0%) for wetlands and uplands, respectively. Those figures intended to demonstrate the high variability of IR during different seasons and storm events. The monthly summary of interception loss from wetlands and uplands will be discussed in the 'Water Balance' section along with other hydrologic components.

Soil Moisture Content

A typical partially saturated soil profile in flatwoods with a groundwater table has three zones: unsaturated, capillary fringe and saturated zones (Figure 4.5). Water in the unsaturated zone is under a suction force due to adhesion and cohesion forces among water

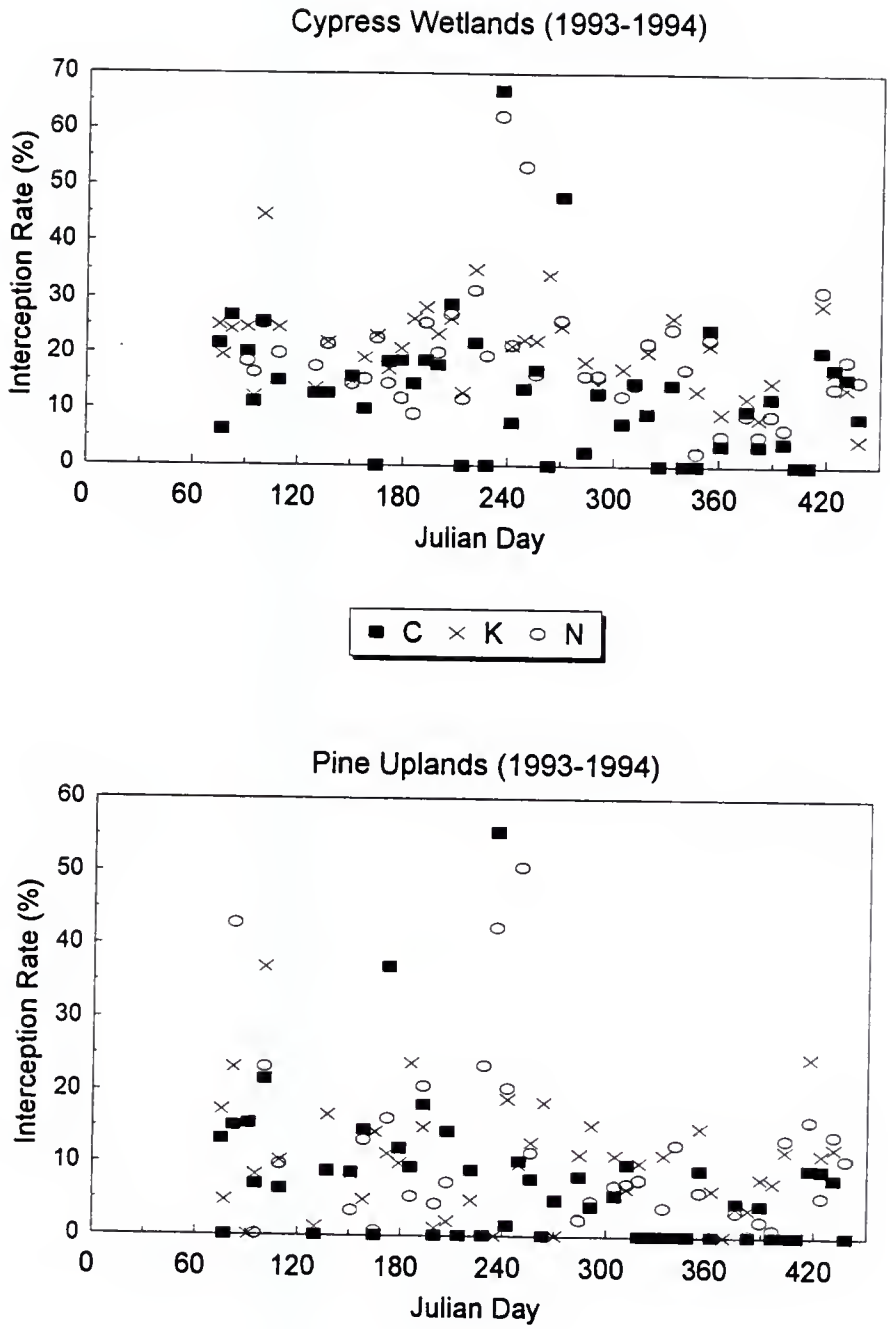


Figure 4.4. Seasonal variation of interception rates for wetlands and uplands during 1993-1994.

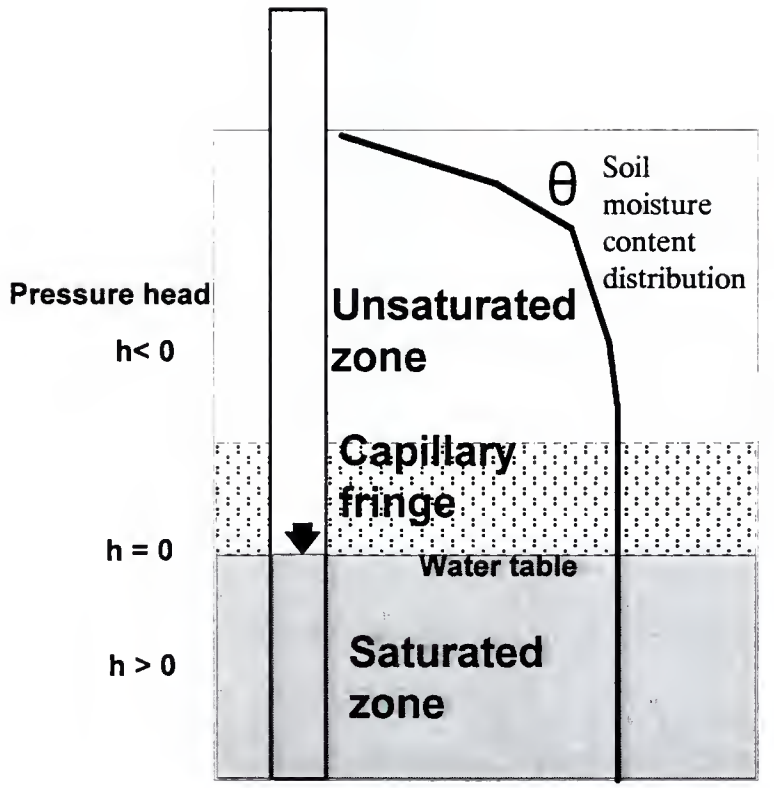


Figure 4.5. A hypothetical soil profile in pine flatwoods showing the unsaturated water zone, capillary fringe, water table, saturated zone, and soil moisture content distribution.

molecules and soil particles, and thus water pressure is less than the atmospheric pressure. The capillary fringe is the transition zone from the unsaturated zone to the saturated zone or the water table aquifer. In a micro-scale view of a soil column, this zone is not of uniform thickness because the capillary rise of water depends on the radius of soil pores as modeled by Romanov (1968). In the literature, the capillary fringe is also termed as the tension-saturated zone since it is quasi-saturated but the pore water is held under tension by molecular forces (Freeze and Cherry, 1979; O'Brien, 1982). A rapid water table rise following a minor application of moisture was observed when this tension-saturated zone extends to the soil surface under high water table conditions (Gillham, 1984). The water table is defined as the surface in the soil/groundwater system where pore water is at atmospheric pressure. The water in the saturated zone is under hydrostatic pressure greater than atmospheric pressure and the volumetric water content is approximately equivalent to soil porosity. However, under most field conditions entrapped air prevents water content actually reaching the soil porosity. Water table levels represent the lower boundaries of the capillary zone when measured in wells that function as very large soil pores.

The importance of soil moisture and the capillary fringe on runoff generation and solute transport has been recognized and emphasized (O'Brien, 1982; Novakowski and Gillham, 1988). Tracer tests showed that 50-90% of storm water was from pre-event 'old' water rather than the new rain water, and the miscible displacement process of translatory flow allowed soil moisture to be displaced quickly down to the water table and to adjacent streams. This observation has been used to explain the fast response of stormflow in forested watersheds where overland flow rarely occurs because of high infiltration rates. Lateral

unsaturated water flow and 'interflow' through connected macropores is not expected to be significant in flatwoods due to the low topographic gradients, except in wetland margin areas. However, the response of the shallow groundwater table to storm events or the vertical movement of water may be greatly affected by initial soil moisture content.

Spatial Distribution

The spatial distribution of soil moisture content was investigated in lateral direction at 25-m intervals from the cypress wetland to the pine upland and vertical direction from 20 cm down to 100 cm in two transects established in the C wetland/upland system (Figures 3.7 and 3.9). Only data collected under unsaturated conditions were used for comparisons between different layers and sites.

Duncan's test by ANOVA for the two transects showed that the soil moisture content at the 25-cm depth in the wetland site was significantly higher at a 95% confidence level than that of the wetland margin and upland sites. Overall the average soil moisture contents of the wetland margins and upland sites were not statistically different from each other although the values at the wetland margin spot was much higher than in the upland in transect #1. The wetland margin sites showed significantly higher values in the transect #2 while transect #1 did not. Soil moisture content at the 75-cm depth in the wetland margin site was significantly higher than that in the upland. As a result, the average annual soil moisture regime in the wetland-upland systems showed an increasing trend from the surrounding pine upland to the wetland (Table 4.1). This soil moisture gradient increased when the water table lowered during dry periods. Surprisingly, the soil moisture content in the 0-25 cm layer at

Table 4.1. Average soil moisture content (SMC %) and water table depth during June 1993 - January 1994 in two transects of the C system.

Site	Layer	ES Transect (#1)		Water table depth (cm)	NW Transect #2		Water table depth (cm)
		SMC	STD†		SMC	STD	
Wetland	25 cm	23.9	4.1	44	---	---	---
Margin	25 cm	21.5	4.8		12.5	9.2	
	45 cm	12	3.9	91	22.2	5.6	85.5
	75 cm	29.2	2.7		---	---	
Upland	25 cm	7.0	2.4		9.4	4.3	
	45 cm	7.9	2.3		11.6	7.3	88.2
	75 cm	19.7	4.8	>100	19.2	4.2	
	100 cm	24.4	6.4		---	---	

†STD = standard deviation.

the wetland margin site in transect #1, was much higher than in the 25-45 cm layer (Table 4.1 and Figure 4.6). This might be explained by: (1) the surface layer had higher organic matter and lower bulk density than the second layer thus containing more soil moisture; and/or (2) plant roots (mainly saw palmetto) in the 25-45 cm layer extracted more water from the lower layer than the upper layer. The margin site of transect #2 did not show this difference, possibly due to a higher water table most of the time and low vegetation density at this particular point.

Wetland soils, which had higher water holding capacity due to higher organic content, showed high water content throughout the investigation period even during the very dry summer in August 1993 (soil moisture content > 15%), when the water table was more than 1 meter below the soil surface. This high soil moisture content may also suggest that

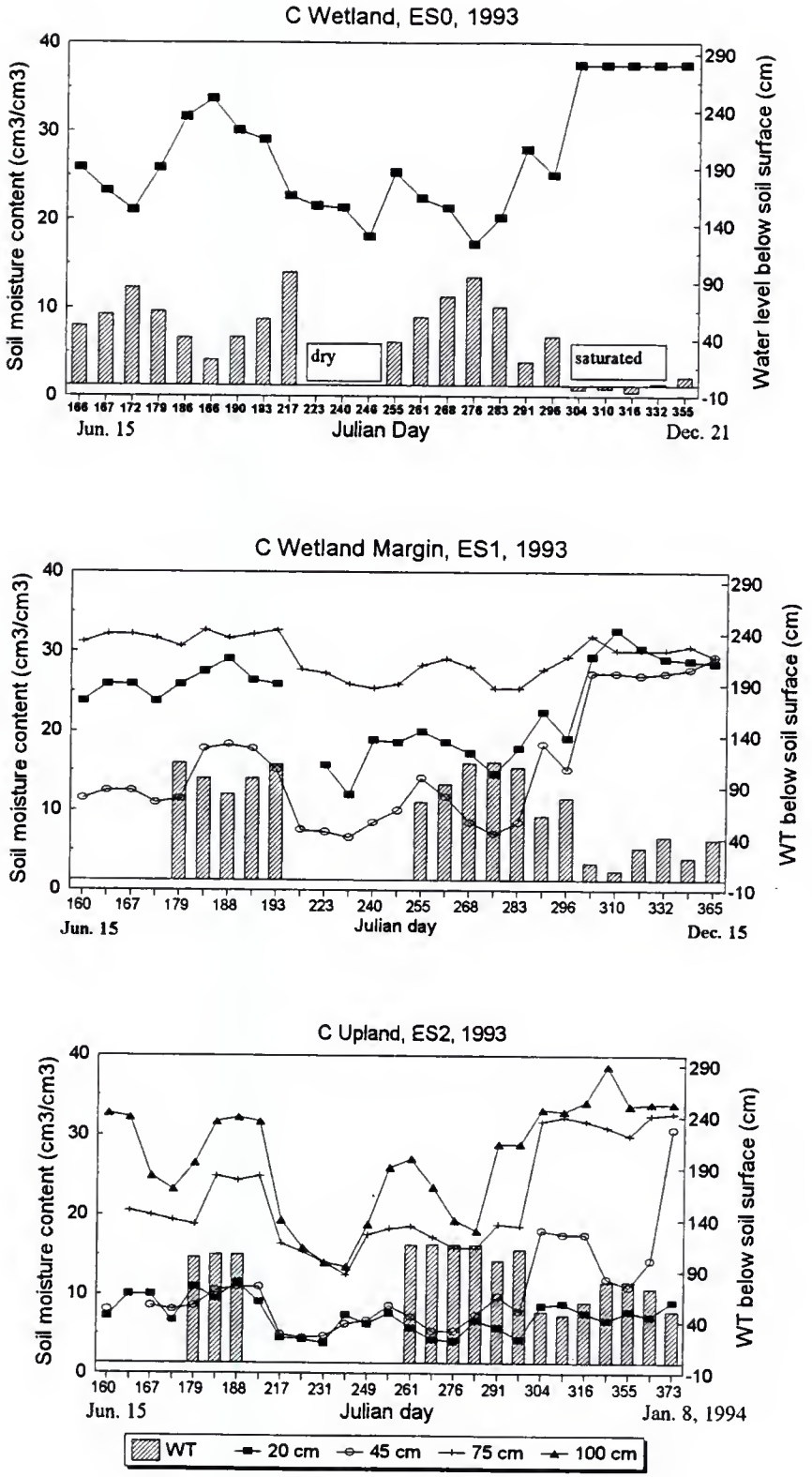


Figure 4.6. Soil moisture content (%) dynamics for the ES transect (#1).

evaporation rates of cypress wetlands were lower than that of the uplands if the transpiration rates of the two systems were similar (Riekerk et al., 1995). Two mechanisms might contribute to this observation: (1) less air movement and lower temperatures in dense wetlands than in open uplands; and/or (2) inhibition by undecomposed litter mulch layer on the pond soil surface.

Seasonal Patterns

Seasonal patterns of soil moisture content closely traced the water table depth (Figures 4.6 and 4.7) with the low in the summer and the high in winter months during 1993. The soil moisture content of the 0-25 cm layer of the upland had lower average values and lower variability, suggesting that the saturated water table zone had little effect on this layer. Water loss due to either ET or internal drainage from the first layer was rapid and soil moisture content was not favorable for plant use during most of the year. In contrast, because of the high water table, soil moisture content at the wetland margin sites was mainly controlled by the water table. Later in this chapter, it has been demonstrated that during dry seasons wetland margin areas could be recharged by wetland surface water, thus more water is available for water loss. In upland soils, the second layer at the 45-cm depth had patterns similar to the first layer when the water table was below 100 cm in the summer, but the moisture content increased dramatically when the water table was above the 100-cm depth in the winter. This was partly caused by the pronounced capillary fringe effects and reduced ET in the winter seasons. The third and the fourth layer at the 75-cm being close to the

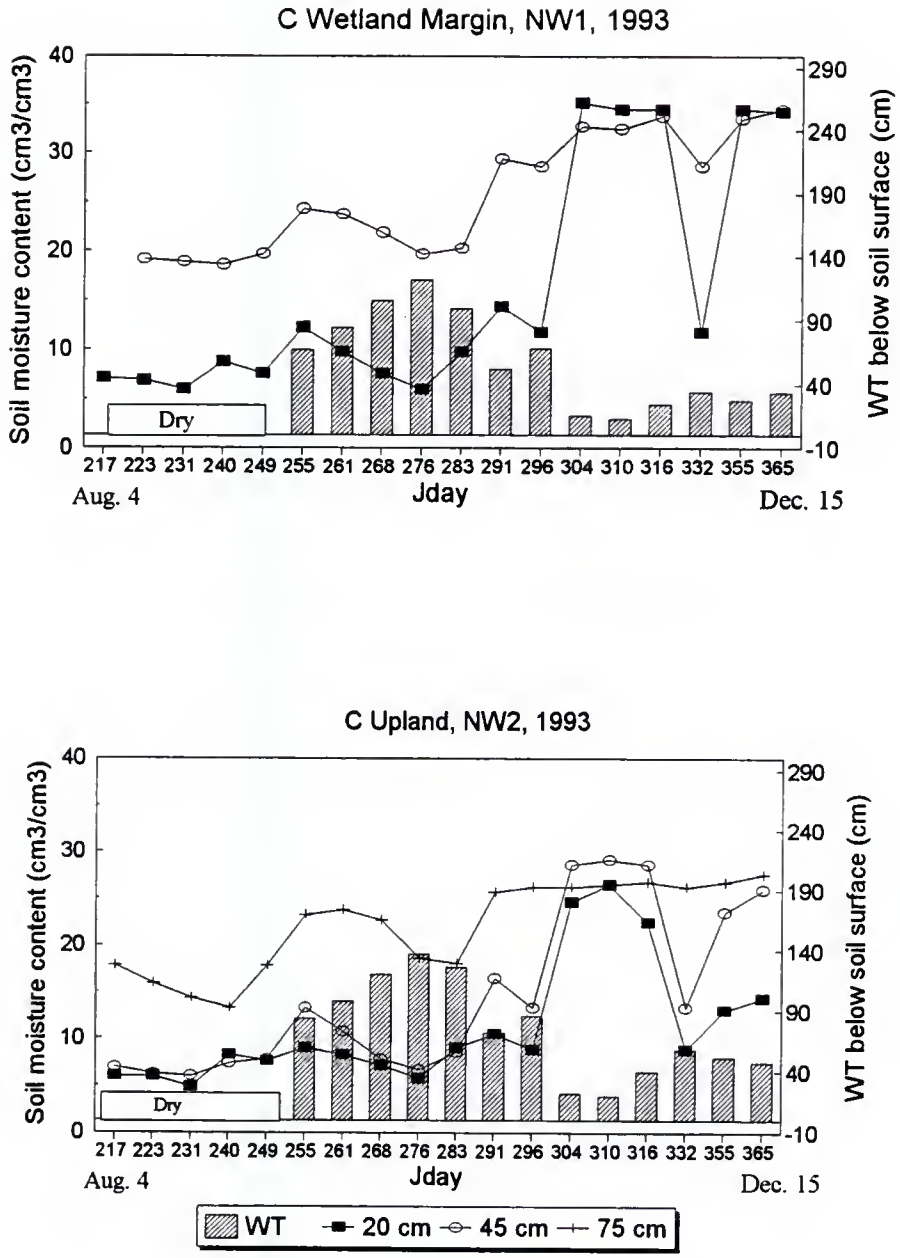

C Wetland Margin, NW1, 1993
Soil moisture content (cm3/cm3)
WT below soil surface (cm)
Dry
217 223 231 240 249 255 261 268 276 283 291 296 304 310 316 332 355 365
Aug. 4
Jday
Dec. 15
C Upland, NW2, 1993
Soil moisture content (cm3/cm3)
WT below soil surface (cm)
Dry
217 223 231 240 249 255 261 268 276 283 291 296 304 310 316 332 355 365
Aug. 4
Jday
Dec. 15
WT
20 cm
45 cm
75 cm

Figure 4.7. Soil moisture content (%) dynamics for the NW transect (#2).

groundwater table and 10-cm depths were sensitive to rainfall events, and soil moisture decreased slowly presumably due to less water loss by root extraction and close to the water table.

Relationships between Soil Moisture Content and Water Table Depth

In a hypothetical soil moisture profile, such as under a free drainage condition, the soil moisture content increases from the soil surface to the water table level (Figure 4.5). However, the shape of this curve may vary significantly in field conditions depending on the water recharge and discharge history of the soil profile. According to Phillips (1987), when the water table dropped below 50 cm, the upward water flux from the water table to the unsaturated zone was less than ET demand, and soil moisture content decreased more rapidly in the surface layer, eventually altering the soil moisture distribution. For sandy soils with high hydraulic conductivity, the water redistribution of infiltrated rainfall water is rapid. If the water table is close to the soil surface, infiltrated water first reduces water tension in the unsaturated zone until the soil moisture content reaches the soil field capacity, then extra rain water will add to the saturated zone and raise the water table level. In an opposite scenario, when ET exists in the upper layers, upward water flux may satisfy ET demand by reducing water table level but not soil moisture content (steady state). When the water table is deeper, ET may greatly reduce water content in the upper layers (0-45 cm) but less in the lower layer due to the discontinuity of capillary pores and reduced hydraulic conductivity for unsaturated water movement.

Initial soil moisture content of different layers in the unsaturated zone must be

specified in simulation models. In this study, the Van Genuchten equation (1980) of the soil moisture characteristic curve was modified to model the soil moisture content distribution in a soil profile. Van Genuchten's analytical equation was developed to describe the relationship between soil moisture content and soil water suction. The advantage of the Van Genuchten equation instead of other methods (Campbell, 1974; Brooks and Corey, 1966) was that the closed form of the formula (Equation 4.2) allowed the matric potential to approach zero or the gradient dh/d(θ) to become 0:

$$S_e = \frac{\theta-\theta_r}{\theta_s-\theta_r} = [1+(\alpha h)^n]^{-m} \tag{4.2}$$

where,

S_e = effective degree of water saturation;

θ = volumetric soil water content;

θ_s = saturated soil water content;

θ_r = residual soil water content;

h = matric potential;

α, m, n = parameters.

Although previous studies suggested that soil moisture content in different soils had linear or nonlinear relationships with water table depth (Guo, 1989; Young, 1969), the Van Genuchten type nonlinear equation was considered to perform better for sandy soils, especially for the 0-45 cm soil layer. As shown from the field data and its previous analysis, the soil moisture content was not a simple function of the water table depth. Our goal was to establish the relationship between soil moisture content and water table depth in order to

generalize the different responses of soil moisture in different soil layers to water level fluctuations resulting from rainfall events and ET.

The matric potential, h, in Van Genuchten's formula was replaced by d-L to satisfy the basic requirements of this equation, i.e. when h approaches 0, θ equals saturated water content θ_s. The variable d is the water table depth and L is a constant specified for different layers (i.e., 20 cm, 45 cm and 75 cm). The relationship between water content and water table level was developed as:

a) for d>L,

$$\theta = (\theta_s - \theta_{min})[1+(\beta(d-L))^a]^{-b} + \theta_{min} \tag{4.3}$$

b) for d≤L,

$$\theta = \theta_s \tag{4.4}$$

where,

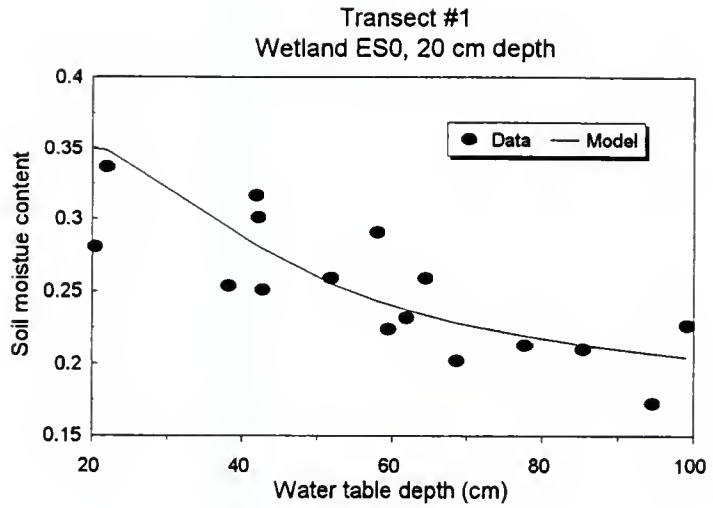
b = 1 - 1/a,

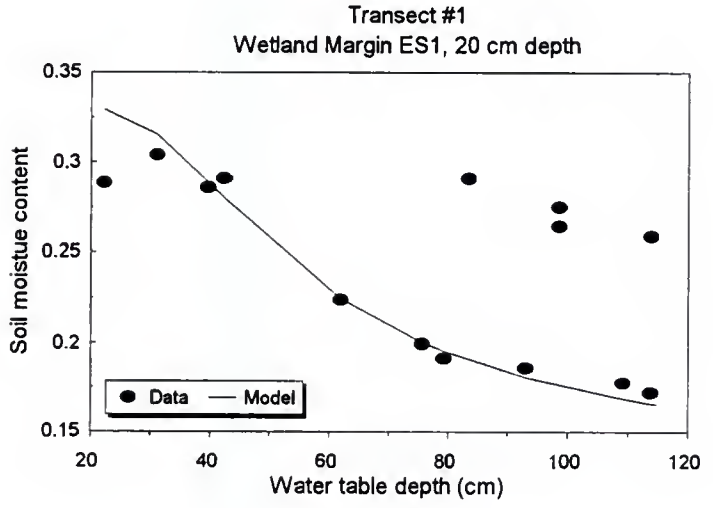
θ_{min} = minimum soil moisture content for the average climatic conditions during the study period. The lower layers had higher values of θ_{min} than the upper layers. The three parameters, a, b, and β were fitted from observed data. Because the water table was above 75 cm in the upland site in the NW transect (#2) most of the time, no modeling was done for this layer. The parameters fitted by the least square method have been summarized in Table 4.2. The relations between soil moisture content and water table depth by field measurements and by Equation 4.3 have been presented in Figures 4.8 and 4.9.

The model fitted well to the observed data as indicated by the high correlation coefficients (R^2), but a few exceptions were noticed. The values of soil moisture content of the wetland margin site in transect #1 showed more scatter (Figure 4.8). The upper portion of the data points with higher values represented a time series of rainfall recharge, and the

Table 4.2. Model parameters describing the relations between soil moisture content and water table depth.

Location		Layer	θ_{min}	θ_s	β	a	R^2
Wetland		20 cm	0.16	0.35	0.0561	1.952	0.59
Margin	Transact 1	20 cm	0.12	0.33	0.0386	2.198	0.95
		45 cm	0.05	0.20	0.0887	1.955	0.84
	Transact 2	20 cm	0.05	0.035	0.0711	2.268	0.79
		45 cm	0.16	0.33	0.0786	1.733	0.82
Upland	Transact 1	20 cm	---	---	---	---	---
		45 cm	0.05	0.2	0.042	2.538	0.89
		75 cm	0.16	0.32	0.0566	1.59	0.78
	Transact 2	20 cm	0.05	0.3	0.0593	2.474	0.91
		45 cm	0.05	0.26	0.1207	1.715	0.88





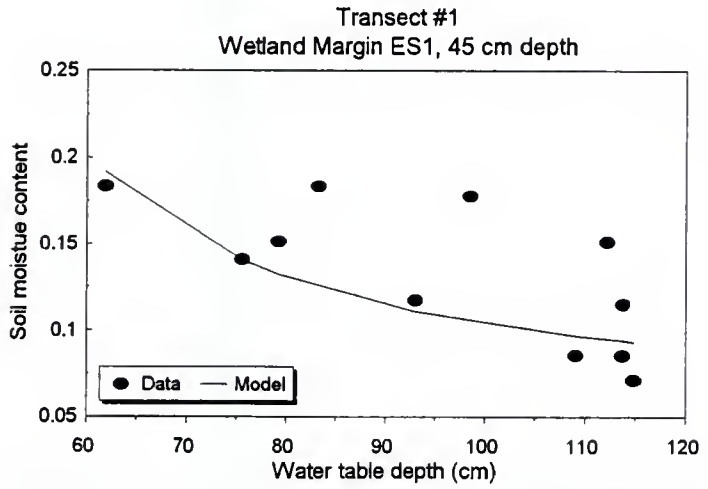
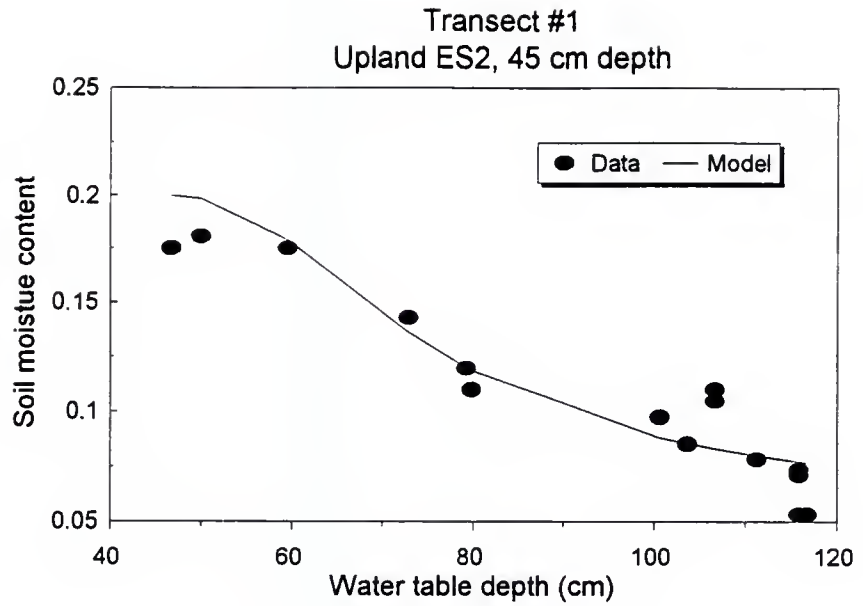


Figure 4.8. Relationships between soil moisture content and water table depth in the ES transect (#1) (to be continued).



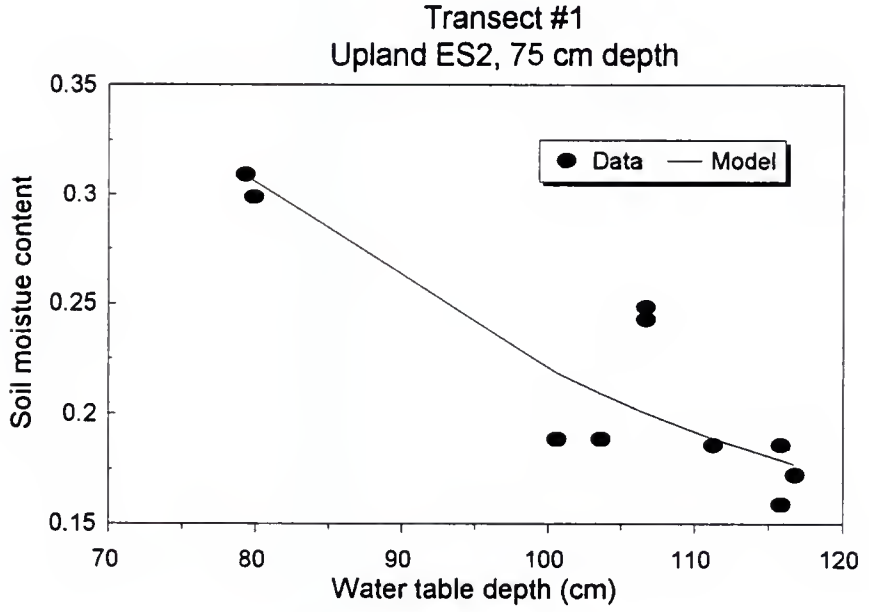
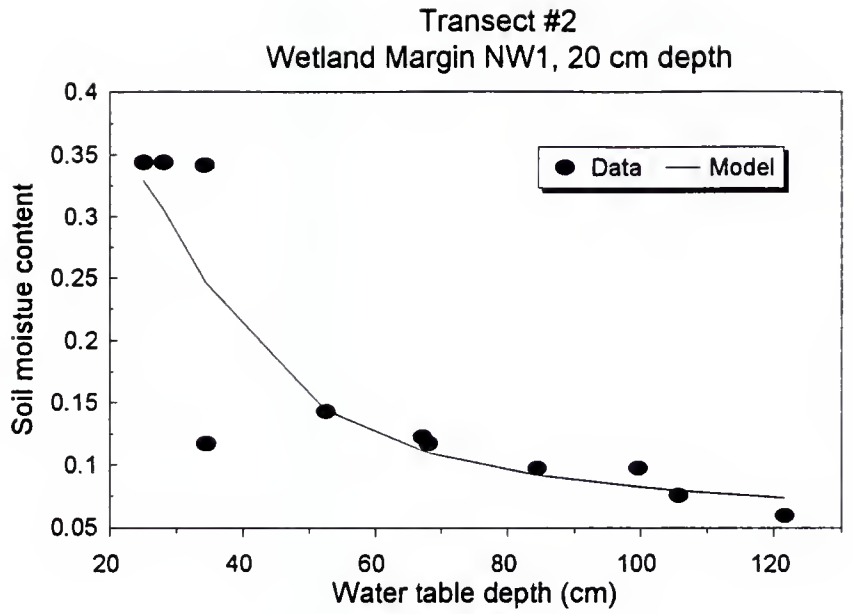


Figure 4.8. (continued).



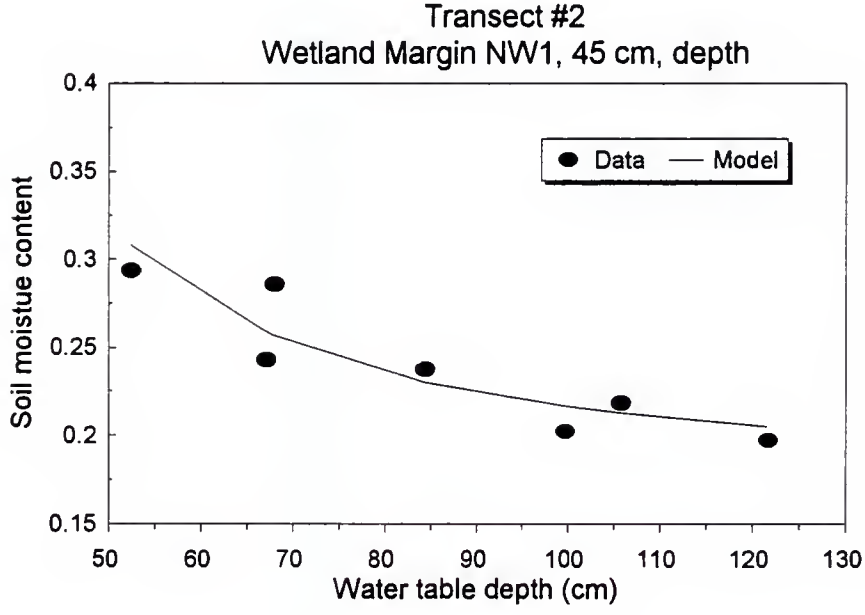
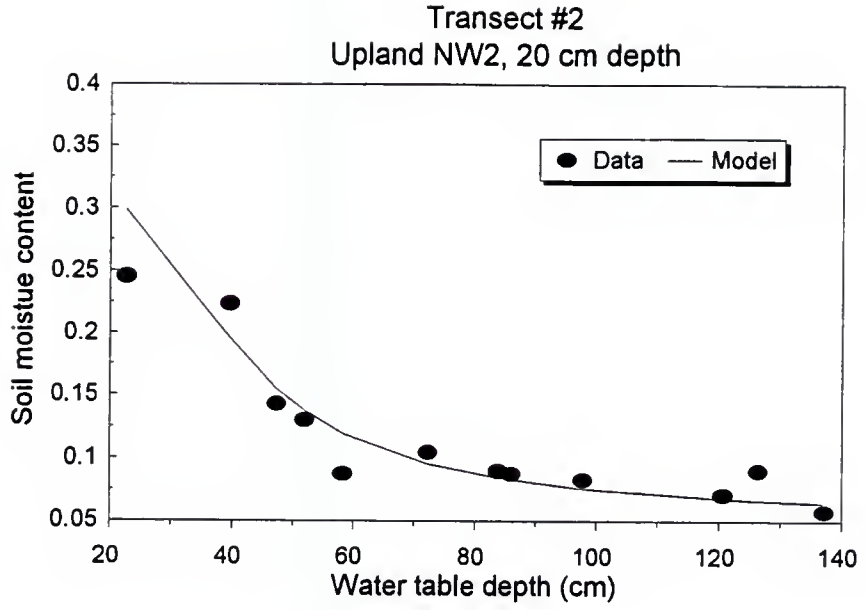


Figure 4.9. Relationships between soil moisture content and water table depth in the NW transect (#2) (to be continued).



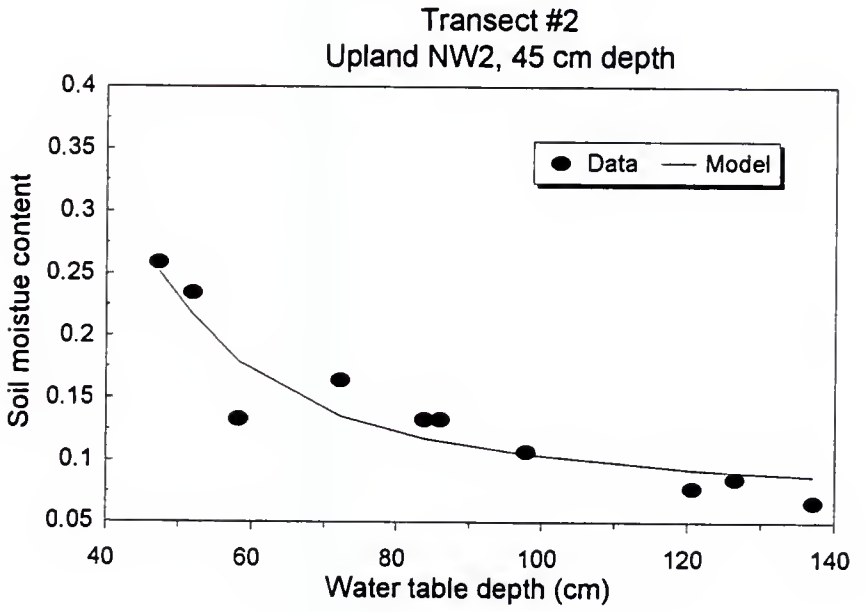


Figure 4.9. (continued).

lower portion of the data represented a time series of water table decline due to ET. This 'hysteresis' phenomena at the pond margin sites reflected the higher retention capacity of organic soils in the surface layers as compared to the sandy upland soils.

The fitted parameters were useful not only for modeling purposes, but also to demonstrate that the characteristics of soil moisture variation in the vadose zone followed water table changes in the saturated zone. The SMC-WT relationships have been plotted in Figure 4.10 using the average values of the parameters in Table 4.2. Those curves were used in the hydrologic model as the input parameters to initialize soil moisture content of each soil layer.

Water Table Dynamics

The temporal and spatial dynamics of water tables in the three wetland-upland systems and interactions between the surface water and the groundwater are presented in this section. Also, controlling factors for the water table rise were analyzed and determined. Because the water table level has a close relationship with the soil moisture content in the unsaturated zone, it may have profound effects on the biological activities (e.g. redox potential, root respiration, decomposition, seed germination), physical processes (e.g. ET, solute movements, mineralization) and chemical transformation (e.g. denitrification) in flatwoods systems. The lateral groundwater movement in this flat terrain essentially is driven by the water table gradients because of the high porosity of the sandy soils. Saturation-induced surface runoff mechanisms dominate flatwoods systems (Heatwole, 1986). Periodic flooding and drought, represented by a high and a low groundwater table

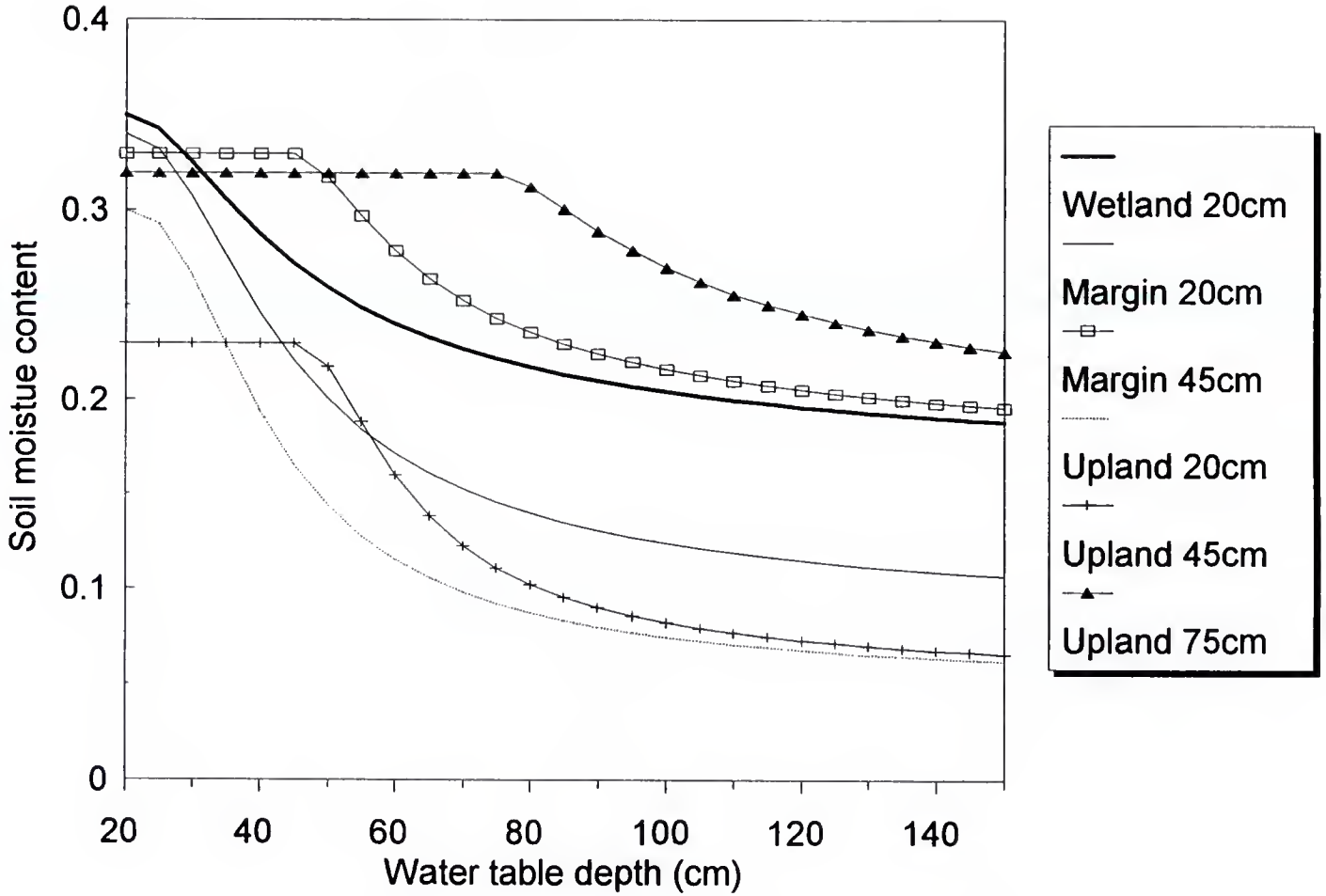


Figure 4.10. Generalized relationships between soil moisture content and water table depth in a wetland-upland system.

respectively, are equally important for amphibians to breed in flatwoods ecosystems (Tanner, 1995). Similarly, seed germination in cypress wetlands needs unsaturated but moist soil conditions, and long term inundation may adversely affect cypress wetlands' regeneration (Brandt and Ewel, 1989).

Temporal Water Level Dynamics

Wetlands

To compare water levels in wetlands, uplands and other significant elevations more effectively, water level elevation (reference to an arbitrary benchmark level for this research site) rather than water level depth was used.

Average daily water level elevations of the three wetlands in 1992, 1993 and 1994 (before May 1) have been presented in Figures 4.11, 4.12 and 4.13. Water levels in the wet year of 1992 had less variation compared with those in the year of 1993, which showed a significant dry-wet pattern. The water level elevation in K wetland showed higher values than in the upland during the spring from March to May and during the late fall in November but lower values during other months. In north central Florida, the spring was normally the driest season due to less rainfall and high evapotranspiration demand. Around late April cypress trees started to leaf out and transpire. The C upland water table levels were always lower than those in wetlands because the upland well was on a topographically lower site. The N upland well was located on a higher elevation site than the wetland well. The water table elevation in this well was higher than that in the pond during wet seasons, but showed little difference during the dry seasons. The alternating high and low values of water level

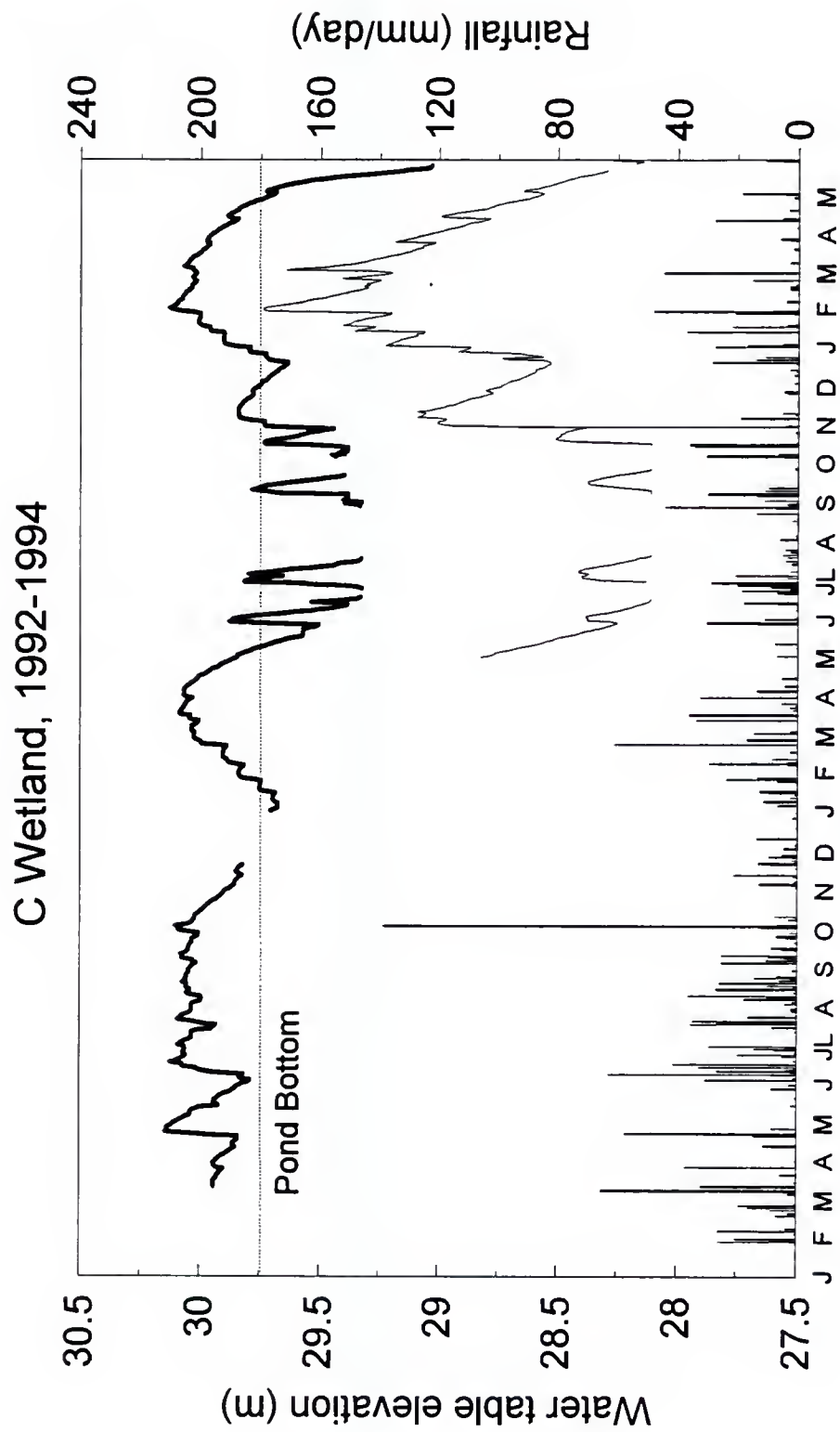


Figure 4.11. Water level dynamics in the C wetland and the surrounding upland from 01-01-1992 to 05-31-1994.

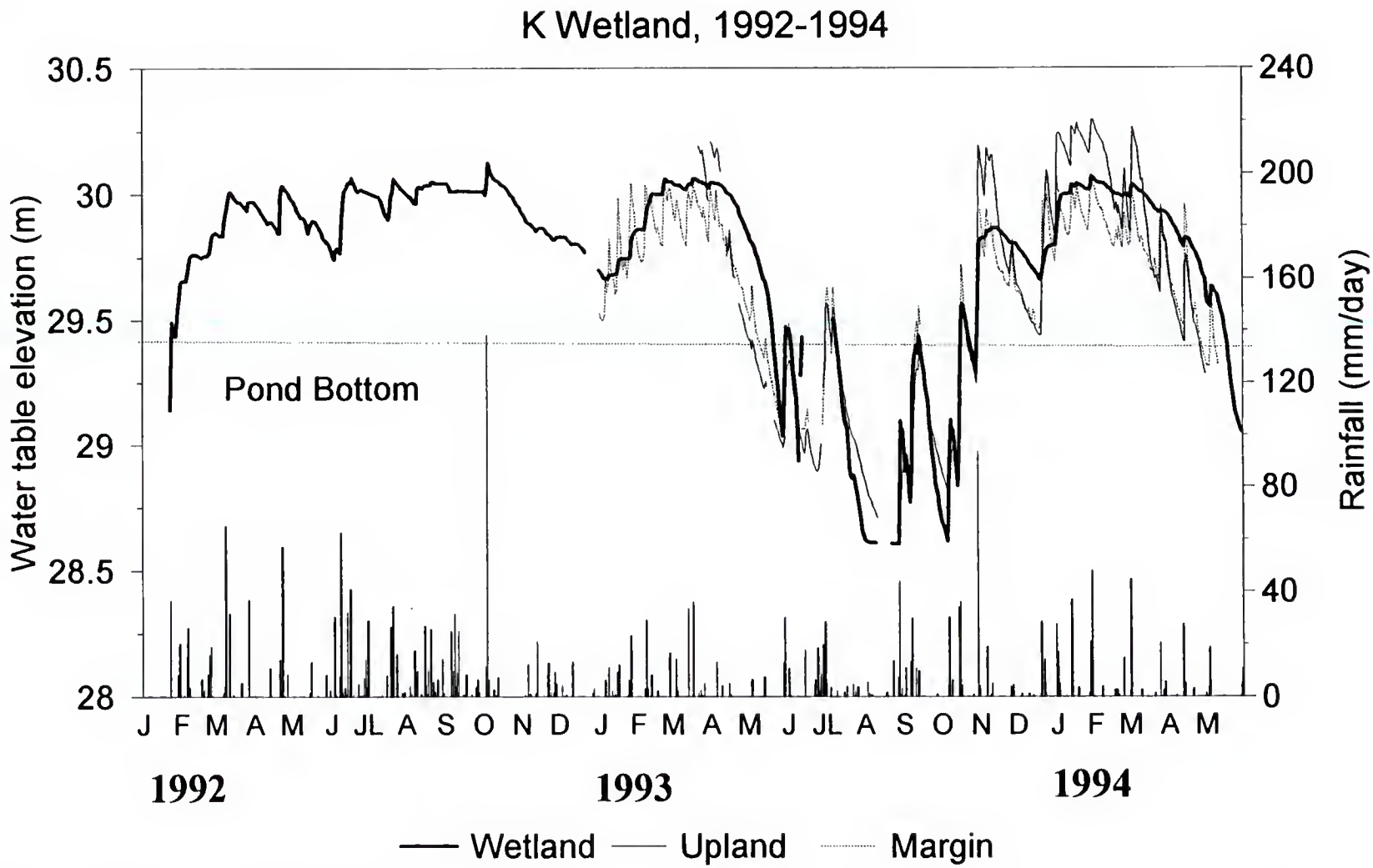


Figure 4.12. Water level dynamics in the K wetland, K margin, and the surrounding upland from 01-01-1992 to 05-31-1994.

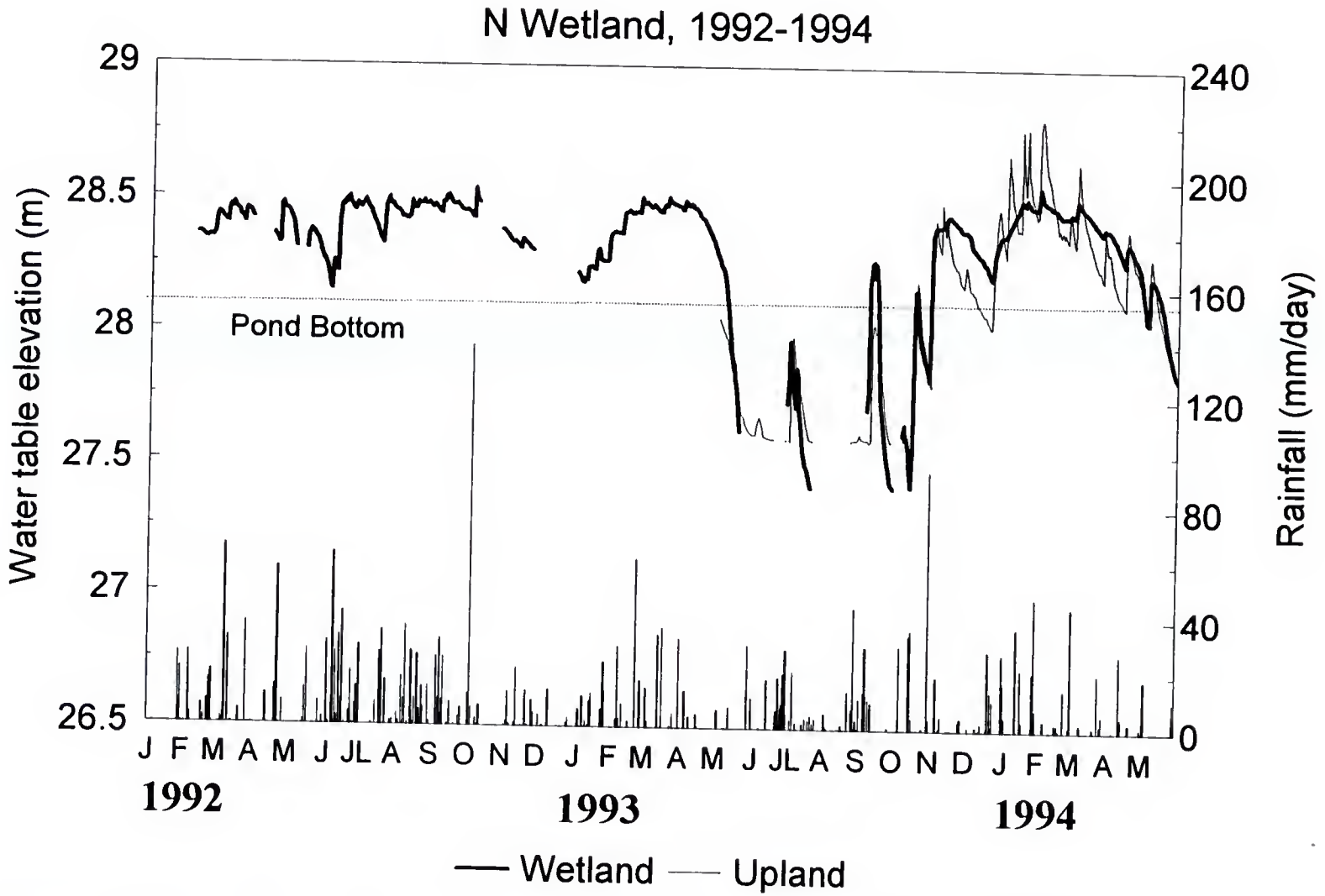


Figure 4.13. Water level dynamics in the N wetland and the surrounding upland from 01-01-1992 to 05-31-1994.

elevations between wetlands and uplands implied that the groundwater flow direction reversed during different seasons. More detailed analyses will be presented later in this Chapter.

Wetland hydroperiod was defined as the duration and frequency of water inundation or flooding during a year. It defines the rise and fall of a wetland's surface and subsurface water (Mitsch and Gosselink, 1986). Although it has been widely used in wetland delineation and identification as the most important hydrologic index of wetland hydrology (US Federal Interagency Committee for Wetland Delineation, 1989), it is still an ambiguous and misleading concept (Best, 1993, personal communication). While the duration (in days) of inundation affects wetland functions, many other properties of the hydrology, such as the continuity of each inundation period, and the residence time and water depth during inundation are also very important for sustaining and developing wetlands ecosystems. To describe the hydrologic characteristics of a dynamic wetland system, such as the cypress domes of the present study conditions, several hydrologic variables require consideration.

A comprehensive index of a combination of three factors for wetland hydroperiod is presented below. These factors are:

1) Duration of wetlands inundation (DI = days of flooding annually);

2) Number of times that continuous inundation (CI) is present annually; and

3) Average depth of inundation of surface water annually (WT in cm).

The first factor, DI, characterizes how long a wetland is flooded and under anaerobic conditions. The second factor, CI, reflects how often the inundation conditions are continuous and how often the soil surface is wet or dry. The third factor, WT, represents the

magnitude of inundation. If daily water table data are available, these three parameters can be calculated by a graphical method. The impacts of forest management practices on the wetland hydroperiod may be quantitatively evaluated with these three variables.

The palmetto line is the distinct transition line from the wetland vegetation to the saw palmetto, an understory of upland pine plantations. The abrupt change of vegetation from wetland to upland species (shortened ecotone) could have been caused by bedding and other surface alterations of upland forest management practices (Clavid, personal communication, 1994). However, Riekerk et al. (1995) suggested that palmetto boundary lines reflected a long term intolerance of the saw palmetto to periodic inundation and/or represented fire boundaries. Field observations reveal that when the water level is higher than the palmetto line, surface flow occurs. The palmetto line might represent the high water table boundary of a cypress pond. Hydroperiod parameters associated with the palmetto line were also included to study maximum inundation characteristics of cypress wetlands.

The three factors for the three wetlands in 1992 and 1993 are summarized in Table 4.3 and Table 4.4, and show that the wetlands had longer duration of inundation (DI), fewer chances of soil surface exposure (CI) and deeper water levels (WT) in a wet year than in a somewhat dry year. Those three indices quantitatively and efficiently demonstrate the variation of wetland hydroperiods from year to year. The hydroperiod analysis with respect to the palmetto line characterized the extreme water table conditions and suggest that wetland outflow occurred more often in a wet year than in a dry year. Among the three wetlands, the C wetland, a relatively isolated wetland, showed higher water table fluctuations and longer inundation. Frequency distributions of the water levels of the three wetlands in 1992 and

Table 4.3. Hydroperiod of cypress wetlands in 1992.

Reference Level	Indicator	C	K	N	Average
Pond Bottom	Duration of inundation (DI), day	---	340	340	340
	Number of continuous inundation (CI)	---	1	1	1
	Average water depth (WT), cm	---	45	32	39
Palmetto Line	Duration of inundation (DI), day	---	119	101	110
	Period of continuous inundation (CI)	---	4	7	6
	Average water depth (WT), cm	---	7	2	5

Table 4.4. Hydroperiod of cypress wetlands in 1993.

Reference Level	Indicator	C	K	N	Average
Pond Bottom	Duration of inundation (DI), day	237	212	201	217
	Number of continuous inundation (CI)	6	4	4	5
	Average water depth (WT), cm	16	21	16	18
Palmetto Line	Duration of inundation (DI), day	55	80	62	66
	Period of continuous inundation (CI)	1	1	1	1
	Average water depth (WT), cm	4	13	2	6

1993 are presented in Figure 4.14 further demonstrate the high variability of wetland hydroperiods in space and time.

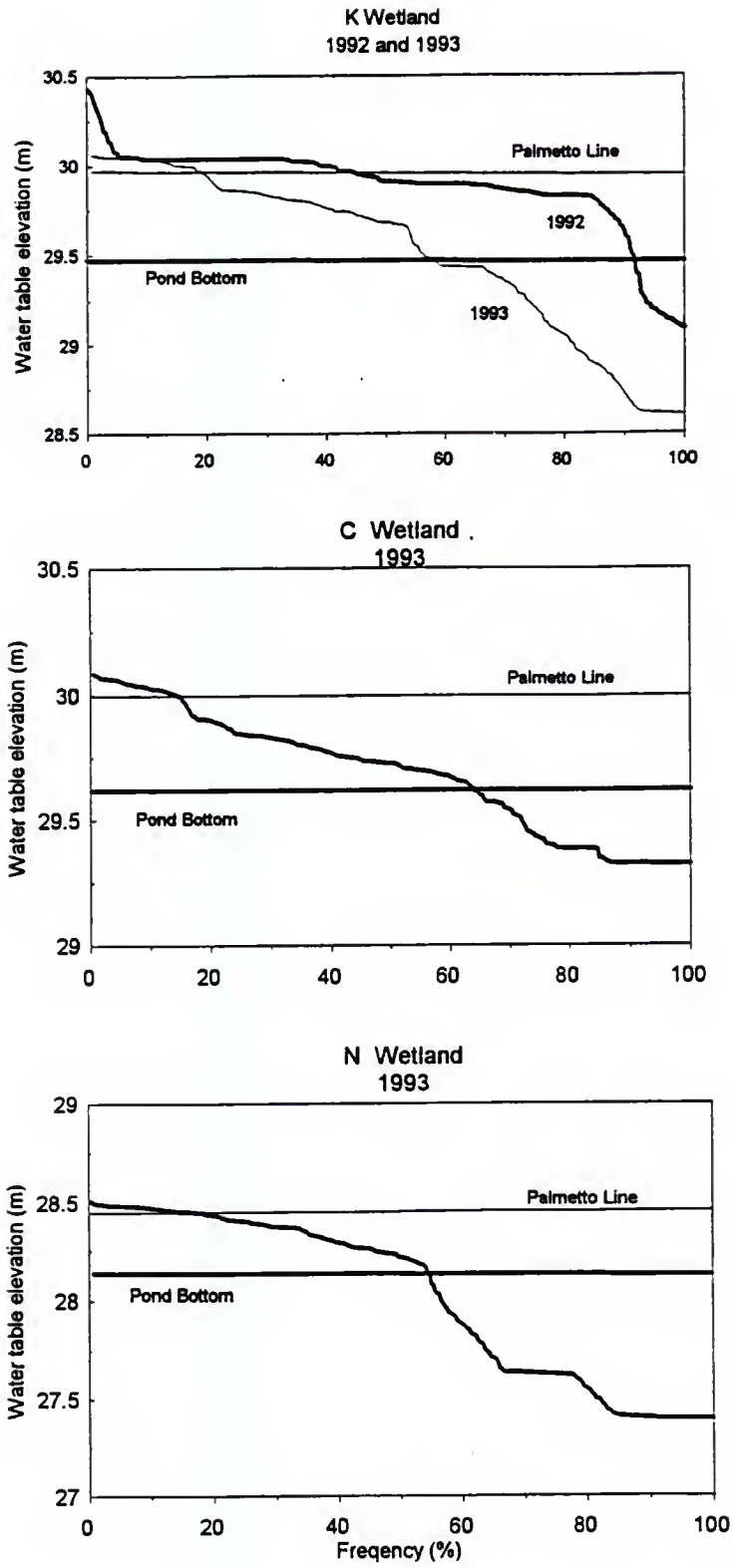


Figure 4.14. Frequency distributions of water level in wetlands.

Uplands

Daily water table dynamics at the three upland sites during May 1993 - April 1994 are also shown in Figures 4.11, 4.12 and 4.13. Associated frequency distributions are presented in Figure 4.15.

Water tables in the upland and margin areas indicate much higher fluctuations than in wetlands when the water levels in wetlands were above the pond bottom. An amplified example is given in Figure 4.16 to compare the different responses to rainfall and evapotranspiration in the K wetland-upland system. Three hypotheses have been postulated to explain this observation.

1) *Lisse effect* and *Wieringermeer effect*;

2) Upland soils have lower storage capacity; and

3) More ET on uplands.

The *Lisse effect* was first named in 1947 by Hooghoudt, who observed a disproportionate water table rise after rain storms in the village of Lisse in Holland (Heliotis and DeWitt, 1987). Rapid water table rise was attributed to air entrapment. Rain water, acting as a tightly closing lid during the infiltration process caused air to become trapped, resulting in an increase of air pressure above the capillary fringe. Therefore, the water level in recording wells or places open to the atmosphere was pushed up to compensate for the air pressure increase in the unsaturated soil zone. Lisse effects are expected to be transient and short-lived because of the fast redistribution of infiltrated water in sandy soils and degassing processes after rainfall. For forest soils with large macropores, the probability of this Lisse effect or 'inverted water table' is low (Gerla, 1992). This mechanism may be more likely to

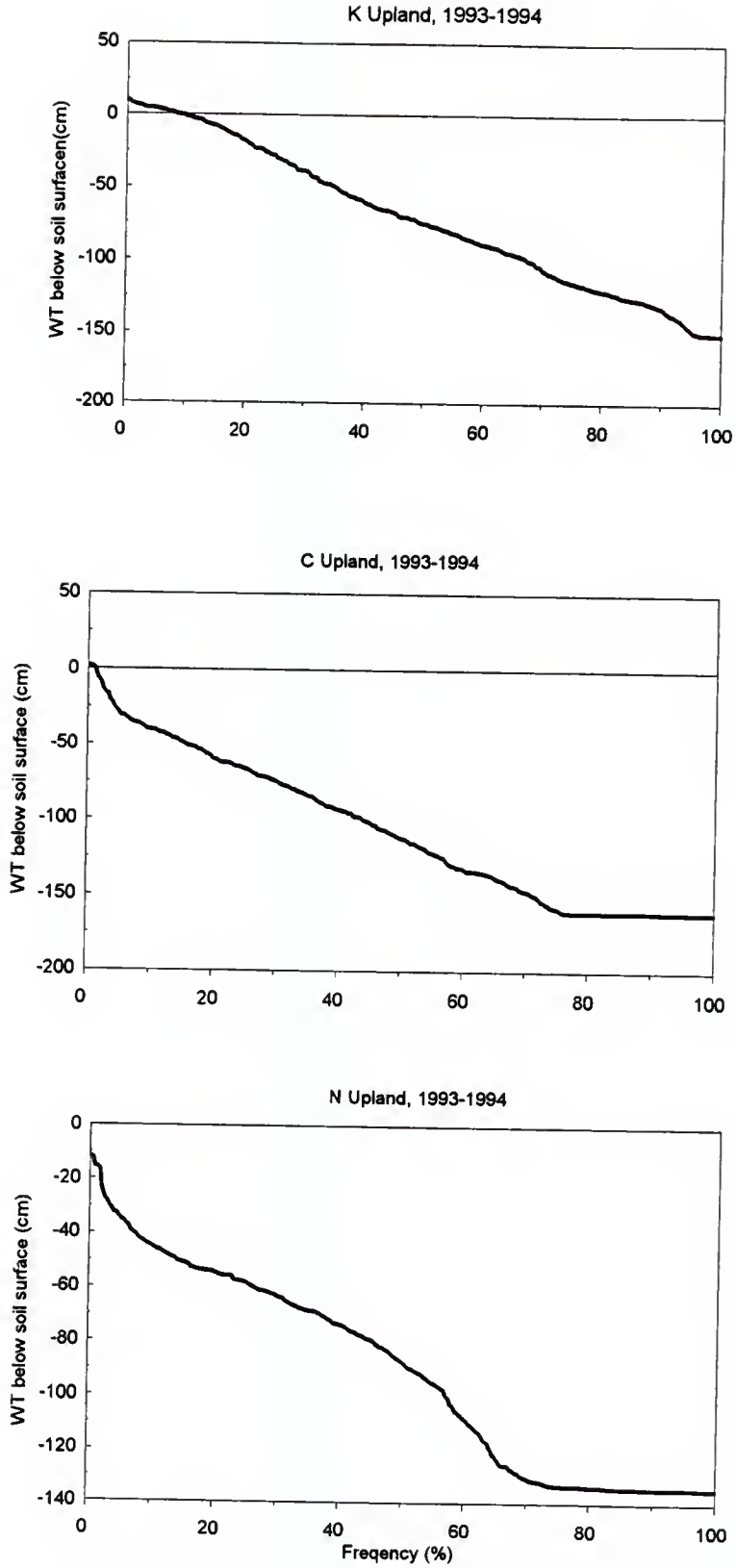


Figure 4.15. Frequency distributions of water table in uplands.

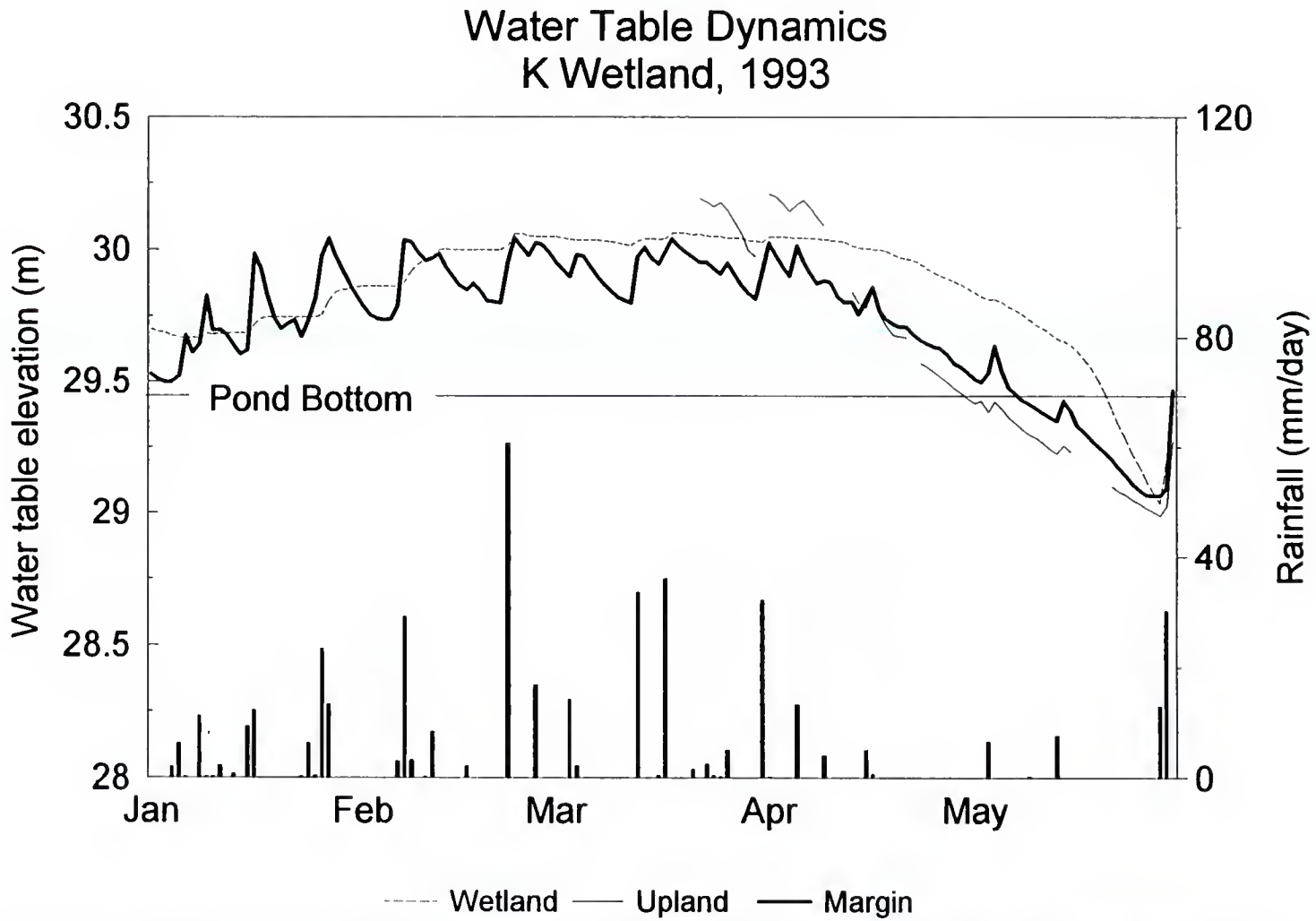


Figure 4.16. A comparison of the water table fluctuation in the wetland, the wetland margin and the upland areas to show: a) the different responses to rainfall and evapotranspiration; b) reversed water table gradients in the spring season.

occur in flatwoods uplands when the water table is below the restricting B_h horizon or when the rainfall intensity is extremely high. The *Wieringermeer effect* was also named by Hooghoutdt in 1947 after the Wieringermeer polder in Holland (Heliotis and DeWitt, 1987). He observed a rapid water table rise or decline during or after the storm when the water table was already high and the capillary fringe was close to the soil surface. It was theorized that as the capillary fringe extended from the water table to the soil surface, adding a small amount of water would convert soil water tension from negative to zero and the capillary water would become phreatic, or free from suction forces locally. Under gravitational forces, the free water would tend to flow into adjacent tension-saturated areas and convert those areas to phreatic zones. Thus, in reality, the water table rise would be higher than that estimated from soil water storage. After the cessation of the rainfall, the water table would decline with almost equal rapidity due to the quick near-surface runoff and evapotranspiration. This mechanism was very likely present in flatwoods systems especially in cypress wetlands and the interface between the wetland and the upland where near-saturation conditions prevail during the year.

The second hypothesis implied that in uplands adding (extracting) 1 cm rainfall (ET) could cause a 4-cm water table rise (drop) for sandy soils with a specific yield of 0.25 as compared with a 1 cm rise of water level in wetlands. Specific yield (S_y) is commonly defined as the volume of water that a soil column can discharge (recharge) per unit surface area of soil per unit decline (rise) of a water table. The specific yield is not a constant and its values for sandy soils could be as low as 0.05 in which case 1 cm of water input/output might generate 20 cm of water table fluctuation. This mechanism may have controlled the

different water table responses in wetlands and uplands.

The third hypothesis stated that more ET from pine uplands than from wetlands could explain the higher water table fluctuation as compared to wetlands. More ET loss would induce more water table drop in uplands. This hypothesis has been shown to be inaccurate on an annual basis (Riekerk et al., 1995), but the seasonal differences of ET between the two systems may play a role. Hypotheses #1 and #2 will be justified later in this chapter.

Several water table depths including the 15 cm, 50 cm, 75 cm, and 120 cm depths are important to wetland delineation and ET processes of flatwoods. With respect to these critical water levels, their frequency distributions for 1993-1994 have been summarized in Table 4.5. The federal manual for identifying and delineating jurisdictional wetlands indicates that if the water table persists continuously within the 15-cm depth of hyperthermic, moderately-drained soils for one week in the growing season the site meets wetland hydrology criteria (1989). The local growing season is from February 14 to December 6 (Dohrenwend, 1978).

Table 4.5. Annual duration of the water table above critical depths in uplands (months).

Upland	Groundwater table depth (cm)				
	15	35	50	75	120
C	0.4	0.9	1.9	3.6	6.6
N	0.1	0.6	1.7	4.9	7.7
K	2.3	3.4	4.2	6.0	10.0
Average	0.9	1.6	2.6	4.8	7.9

Two of the three upland wells barely met these criteria for a dry year during 1993-

1994. The recorder at the K upland was on a depression spot between two planting beds and was 50 m away from the wetland margin. Two continuous week-long periods were recorded when the water tables were within 15 cm in February and March 1994 at this site. The water level at C upland, a drier site, was within the 15-cm depth for 7 days in February 1993. However, the soils at these two sites were identified as non-hydric soils reflecting the dynamic nature of the shallow groundwater table in flatwoods (Kuehl, 1993).

Phillips (1987) reported that when the water table was below 50 cm depth maximum plant root density in the A horizon must absorb water from other layers to realize potential transpiration, and therefore, that the nutrient status below the A horizon could be important for tree nutrition. His study also suggested that when the water table was within 35 cm, the upward flux from the saturated zone to the unsaturated zone was equal to ET from the A horizon. Water tables in pine uplands were located below the 30-cm depth for over 10 months and below 50 cm for 9 months. This suggests that water consumption by plants was mainly from lower layers during a significant time period of the growing season. It was reported that when the water table was maintained artificially at 45 cm it had the most positive effects on slash pine growth (White and Pritchett, 1970). Barnes and Ralson (cited by White and Pritchett, 1970) suggested pine trees grew best where either a fine-textured horizon or mottling occurred at about the 75-cm depth. Apparently, such favorable soil conditions have to be achieved in poorly drained pine flatwoods by engineering methods, e.g. water table control and irrigation (Konyha et al., 1992). The water tables in uplands were below 120 cm for more than four months during the summer season, when water use by plants was mostly restricted to the unsaturated zone.

Monthly water table dynamics based on data collected weekly from wells at the wetland margin and upland areas have been presented in Figure 4.17. The seasonal patterns were pronounced with a low (>80 cm depth on average) during the summer months (May-September) with the highest rainfall, temperatures and ET, and a high (< 10 cm on average) during the winter (January-March) with the lowest temperatures and ET, but with moderate rainfall. Periodic thunder storms in the summer seasons did not raise the water table significantly because of the high available water storage in the unsaturated soil zone and forest canopies. However, in the winter, due to low ET loss, most of the rainfall input was added to the water table aquifer, raising water tables and inducing flooding.

Spatial Distribution of the Water Level

A difference of less than 100 cm between the bottom elevation of a wetland and its surrounding upland significantly alters the vegetation and soil distribution in flatwoods ecosystems due to changes in hydrology. A small depression of a few square meters in pine flatwoods may form a wetland colonized by obligative species such as pond cypress. In this section the spatial distributions of the water table in the wetland-upland continuum extending from the pond margins to the upland have been presented for each system. Water table data along transects for this analysis were collected on a weekly basis from May 1992 to April 1994 (Figure 4.18). The figure shows that in general groundwater table elevations generally followed the surface topography. The regression line with a slope slightly less than 1.0 implied that the high elevation sites in the west part of the research area, where the K and C wetlands were located, generally had lower water table depths than the east site, where the

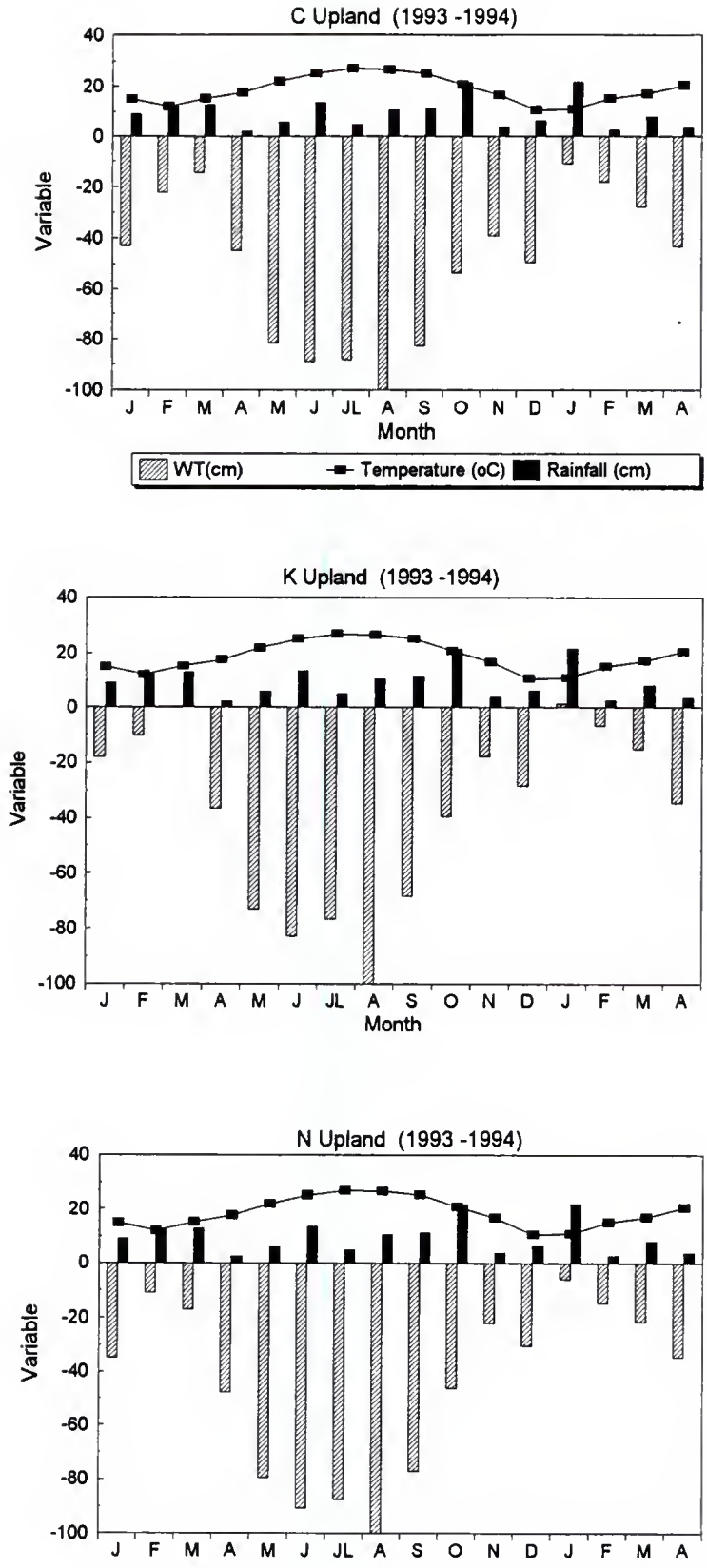

C Upland (1993 -1994)
Variable
Month
J F M A M J JL A S O N D J F M A
WT(cm)
Temperature (oC)
Rainfall (cm)
K Upland (1993 -1994)
Variable
Month
J F M A M J JL A S O N D J F M A
N Upland (1993 -1994)
Variable
J F M A M J JL A S O N D J F M A

Figure 4.17. Seasonal distributions of groundwater table in uplands.

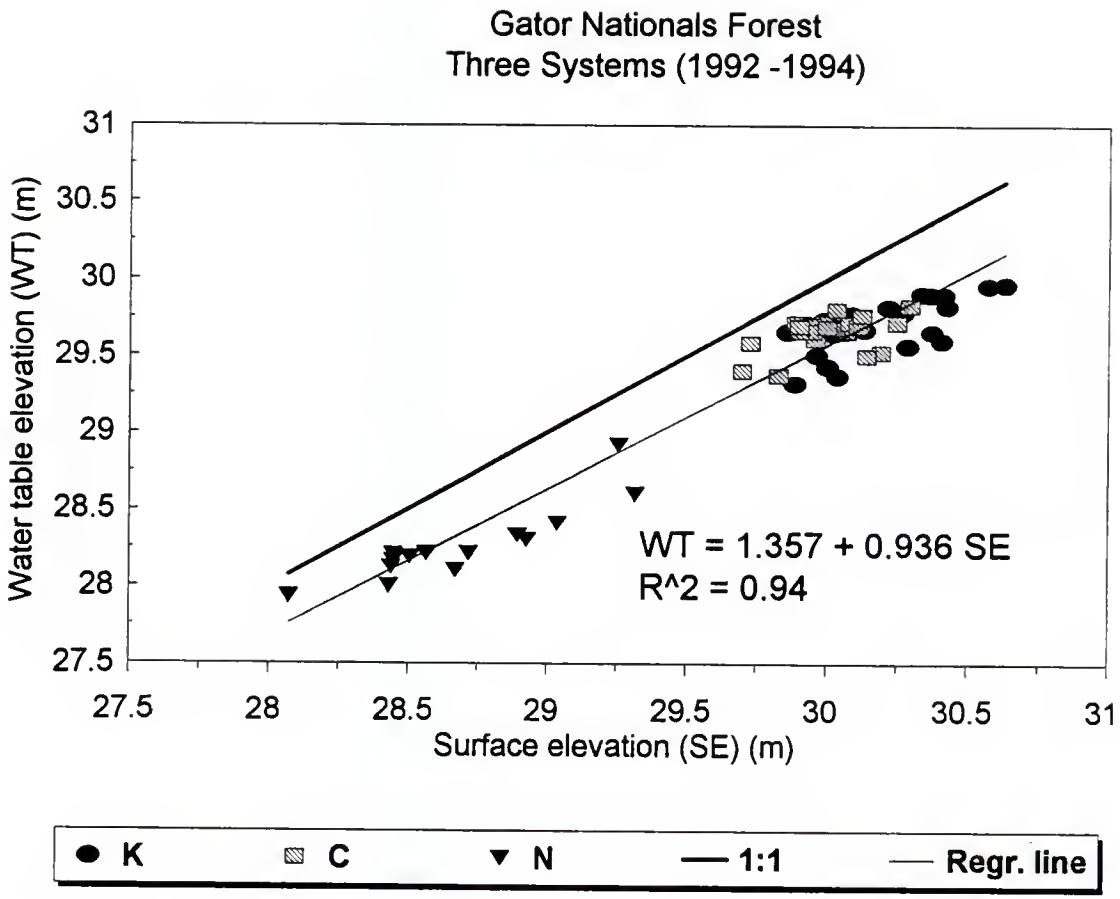


Figure 4.18. The spatial distribution of the water table relative to the ground surface; each data point represents the average water table elevation of three systems during 1992-1994.

N wetland was located. General trends were the same for individual systems (Figure 4.19), but with higher variability, suggesting the complex relations between surface elevation and water table elevation in a local system. The overall parallel pattern between the land surface and the groundwater table suggested groundwater flow through the landscape was generally dictated by the large-scale groundwater pressure gradient, and that single wetland-upland systems had little effect on the general flow patterns. However, the small-scale drop of the water table from the pond margin to the upland (Figure 4.20) suggested that the soil moisture content tended to decrease from the wetland margin to the upland, resulting in gradation of different vegetation types. Caution must be taken in interpreting these data as the graphs represented average conditions over the three years' study period. Furthermore, the deeper water table in uplands than in the wetland margins did not necessarily mean that the groundwater flowed from the margin to the upland since water flow was driven by the total hydraulic head gradient (difference of water table elevation).

Several time sequences of the spatial distribution of the water table relative to the ground surface in two soil cross sections (AA' and BB' in Figure 3.9) have been presented in Figures 4.21 and 4.22 to represent the seasonal dynamics across the landscape of the C wetland.

Water Table Responses to Storm Events and Daily ET

Groundwater tables in flatwoods are most dynamic during storm events and the water table rise may significantly expand the saturation areas in the wetland-upland systems under very wet conditions. Analysis of the diurnal fluctuation patterns due to groundwater flow

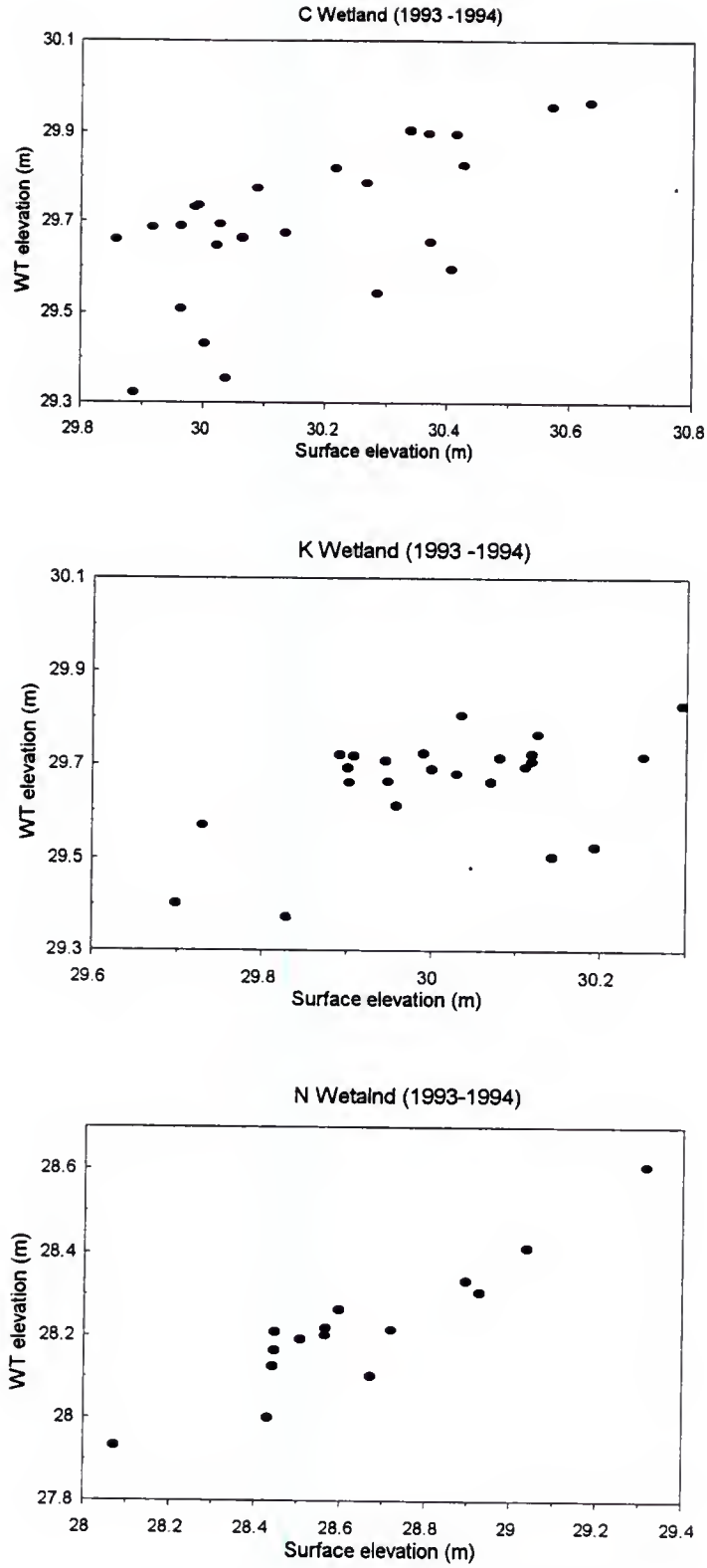


Figure 4.19. The spatial distribution of the groundwater table elevations from the wetland margin to the pine upland in single systems.

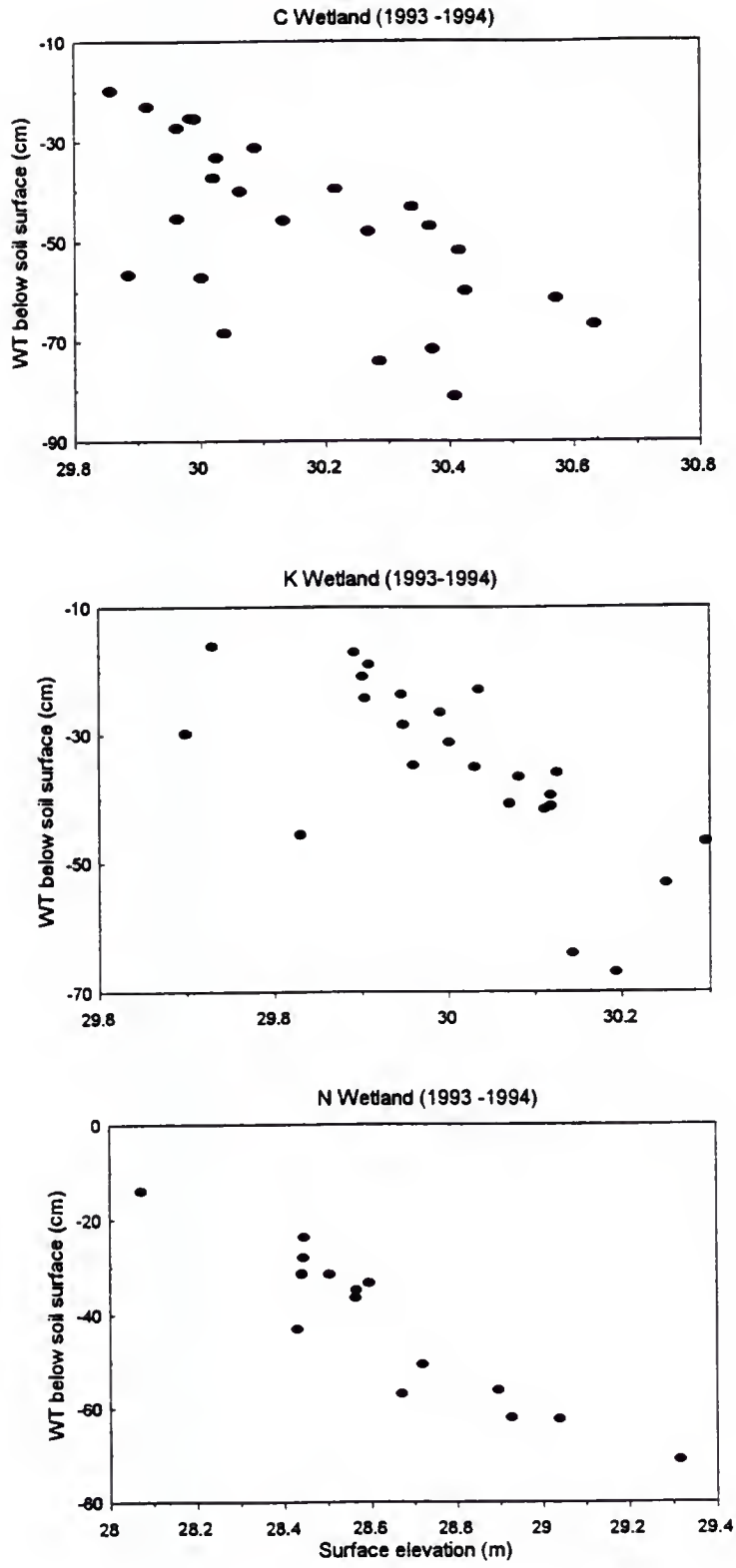


Figure 4.20. The spatial distribution of the groundwater table depth from the wetland margin areas to the pine upland areas to show the drier conditions in pine uplands.

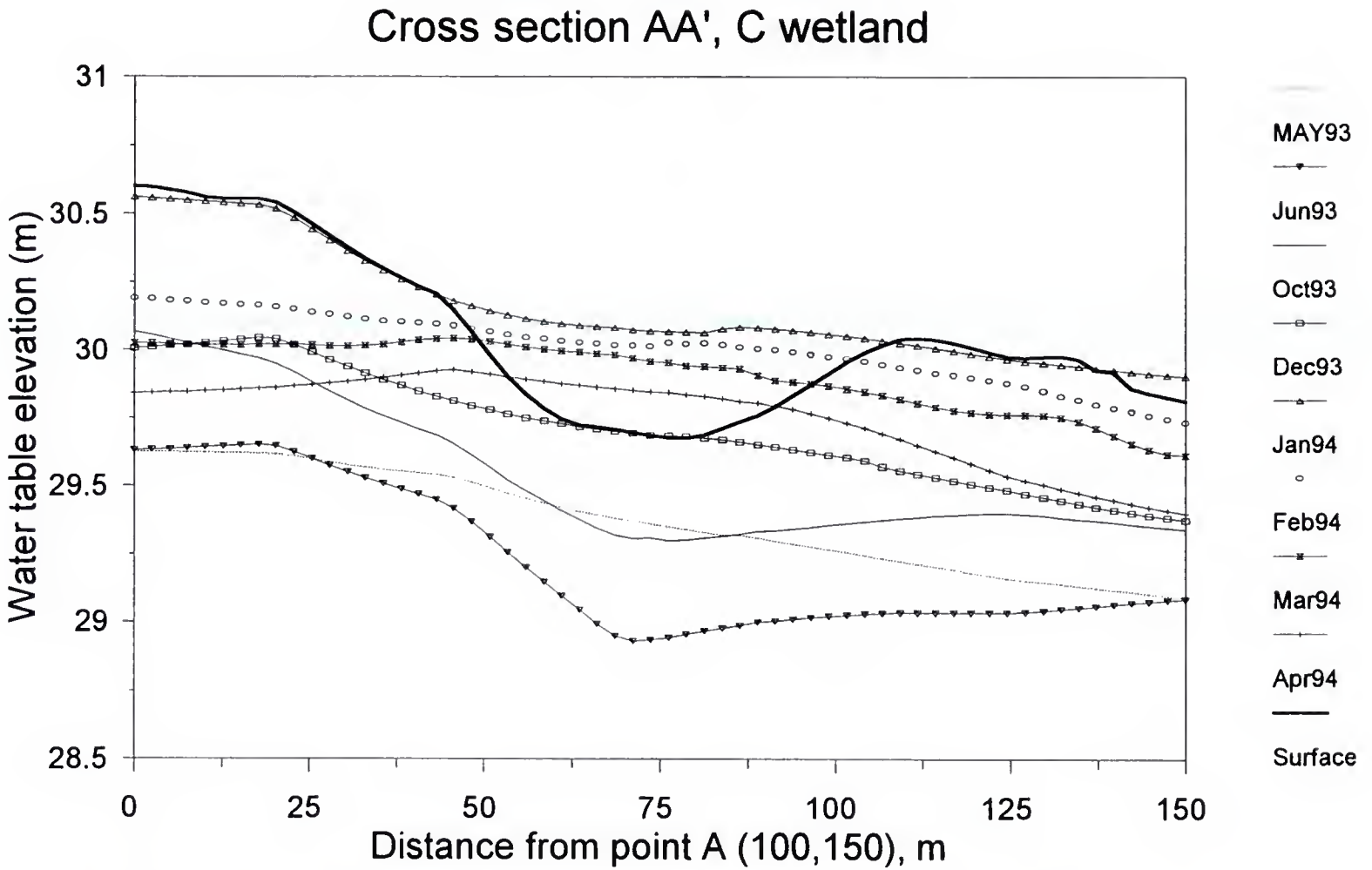


Figure 4.21. Water table profiles in the cross section AA' of the C wetland to show both the spatial distribution and seasonal dynamics of the groundwater table in a wetland-upland continuum.

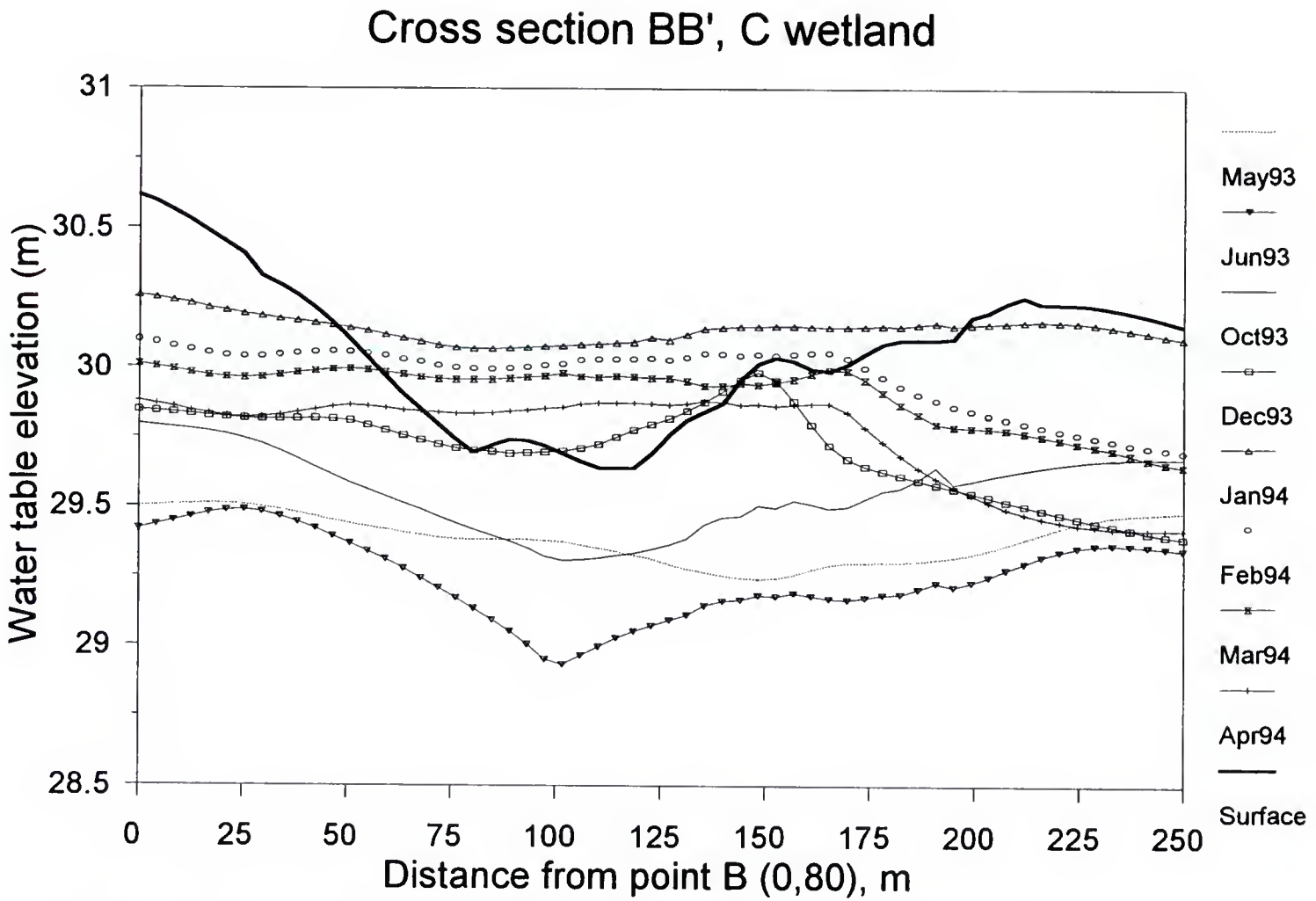


Figure 4.22. Water table profiles in the cross section BB' of the C wetland to show both the spatial distribution and seasonal dynamics of the groundwater table in a wetland-upland continuum.

or ET has been used as a convenient way to estimate ET from wetlands (White, 1932; Heikurainen, 1963; Freeze and Cherry, 1979; Heimburg, 1976; Ewel and Smith, 1993; Rushton, 1994). The following section discusses factors determining the water table rise in a storm event and introduces the variable storativity concept in contrast to the specific yield. Also, the hourly water table variations in wetland-upland systems are analyzed.

Water table rise and specific yield

Temporally continuous water table data of different wetlands and uplands at five locations in a two-hour time scale were used for this analysis. Because water levels in the wetland were close to or above the pond bottom during most of the time, few rainfall events from wetlands were valid for statistical analysis, and, as a result, an averaged value was used for comparison purposes. Figure 4.23 presents selected water table hydrographs for uplands and margin sites for different seasons.

Factors influencing the water table rise. Statistical analysis by general regression and stepwise regression procedures (SAS Institute, 1985) were conducted to determine which factors were most important in controlling the water table rise in flatwoods soils. Dependent variables included water table rise (WTR) in one storm event and water table rise rate (WRR) (cm/hour) which is WTR divided by the time length from the beginning to the peak of the water table rise. Independent variables included total rainfall amount (RAIN), rainfall intensity (RIT), average temperature (TEMP), rainfall index (RI), temperature index (TI), and starting water table depth (START) (Table 4.6). About 23-42 storm events in 1993 and 1994 were selected. The water table fluctuated within the soil profiles and no surface water

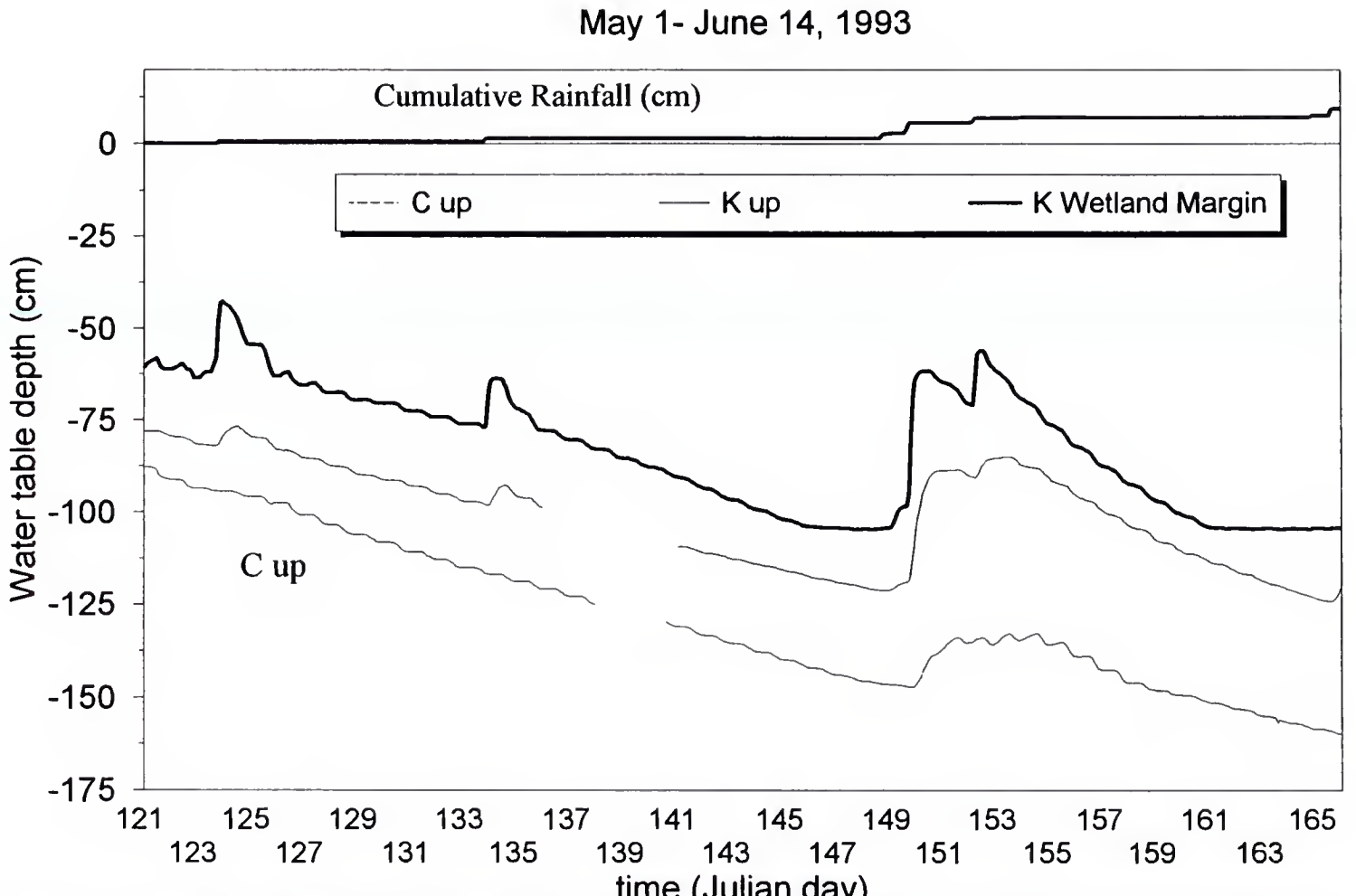


Figure 4.23. Water table hydrographs plotted from recording charts with a 2-hour time interval to show the spatial and temporal responses of the groundwater tables to storm events and evapotranspiration.

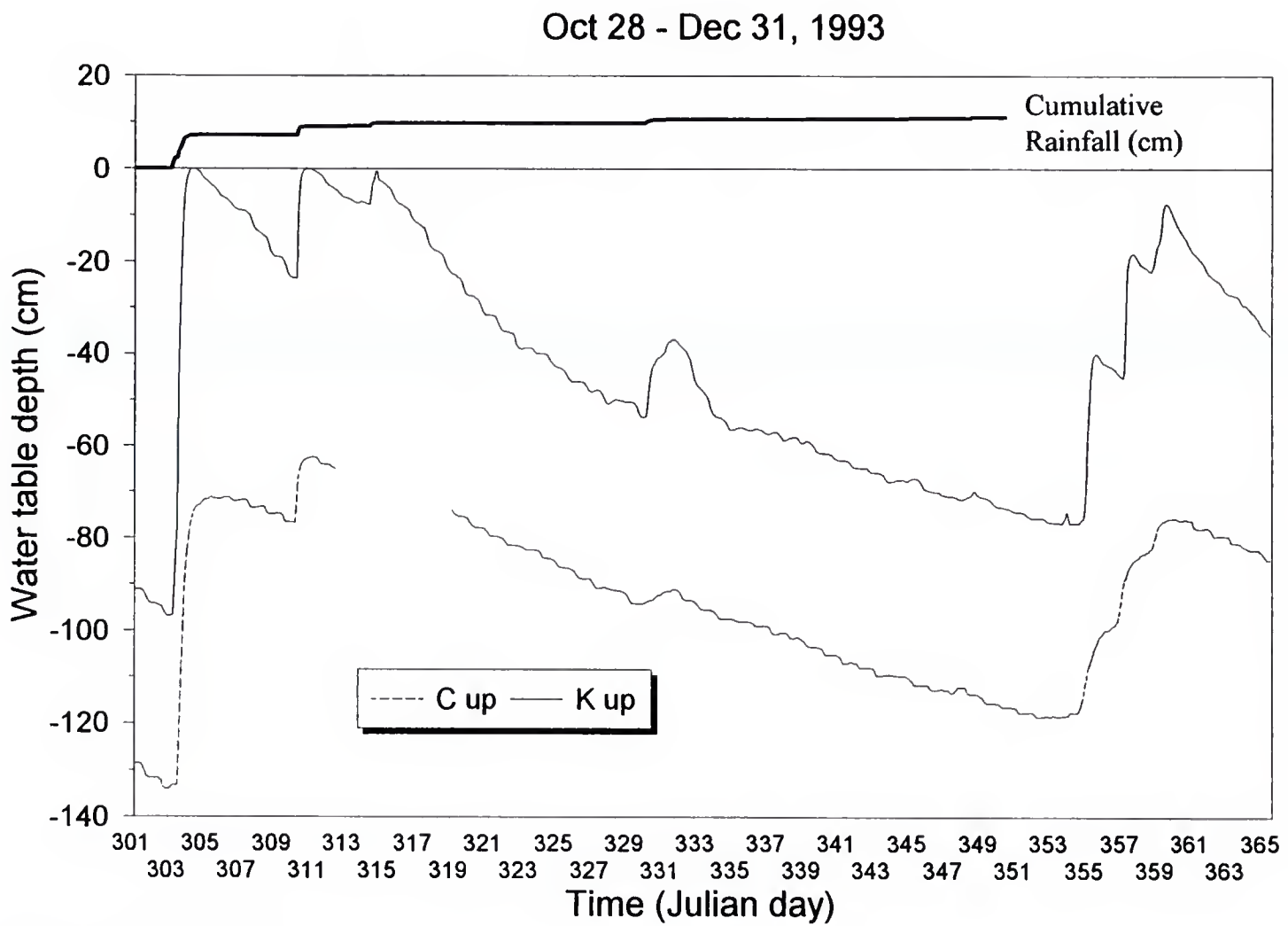
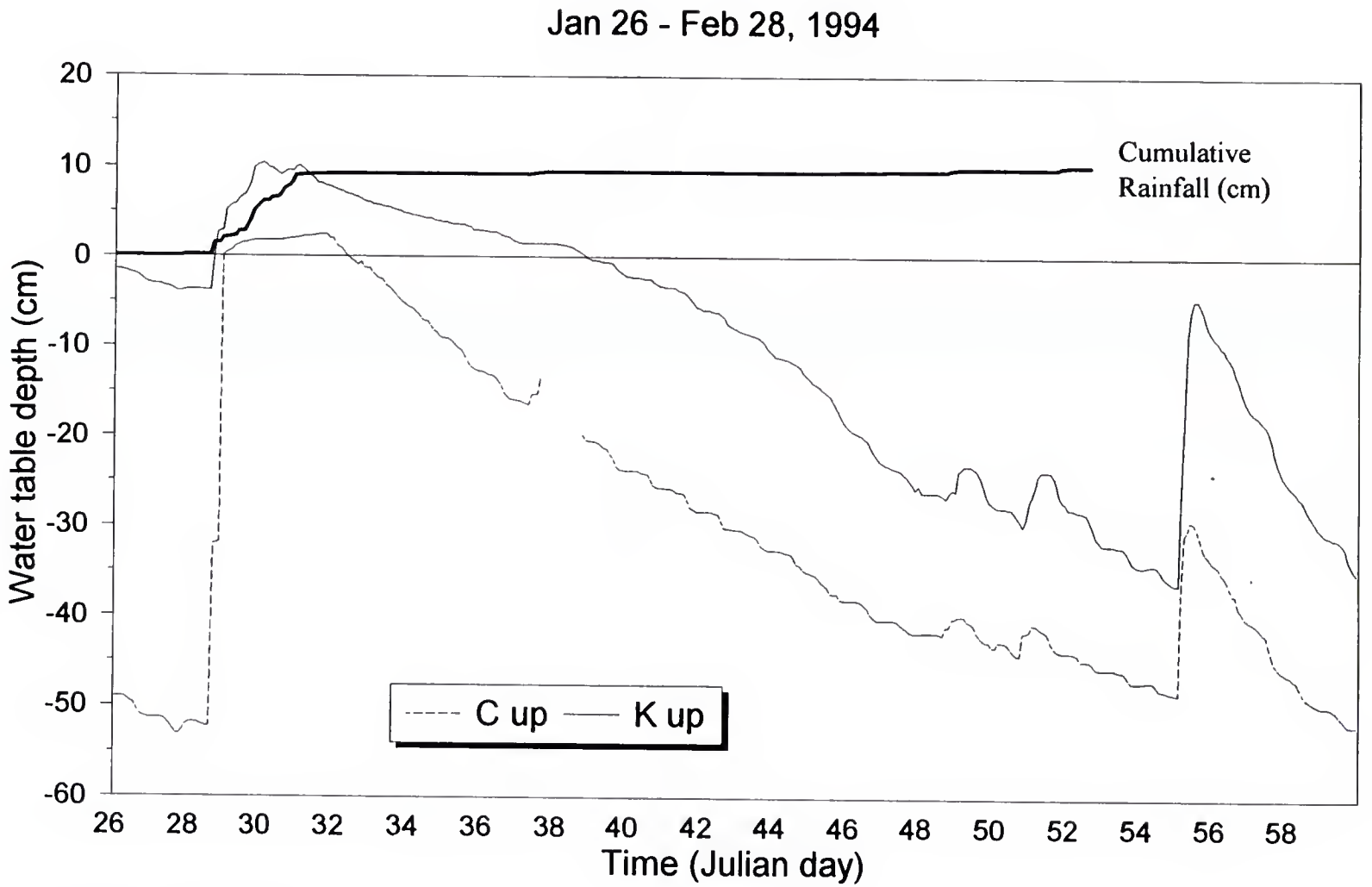


Figure 4.23 (continued)



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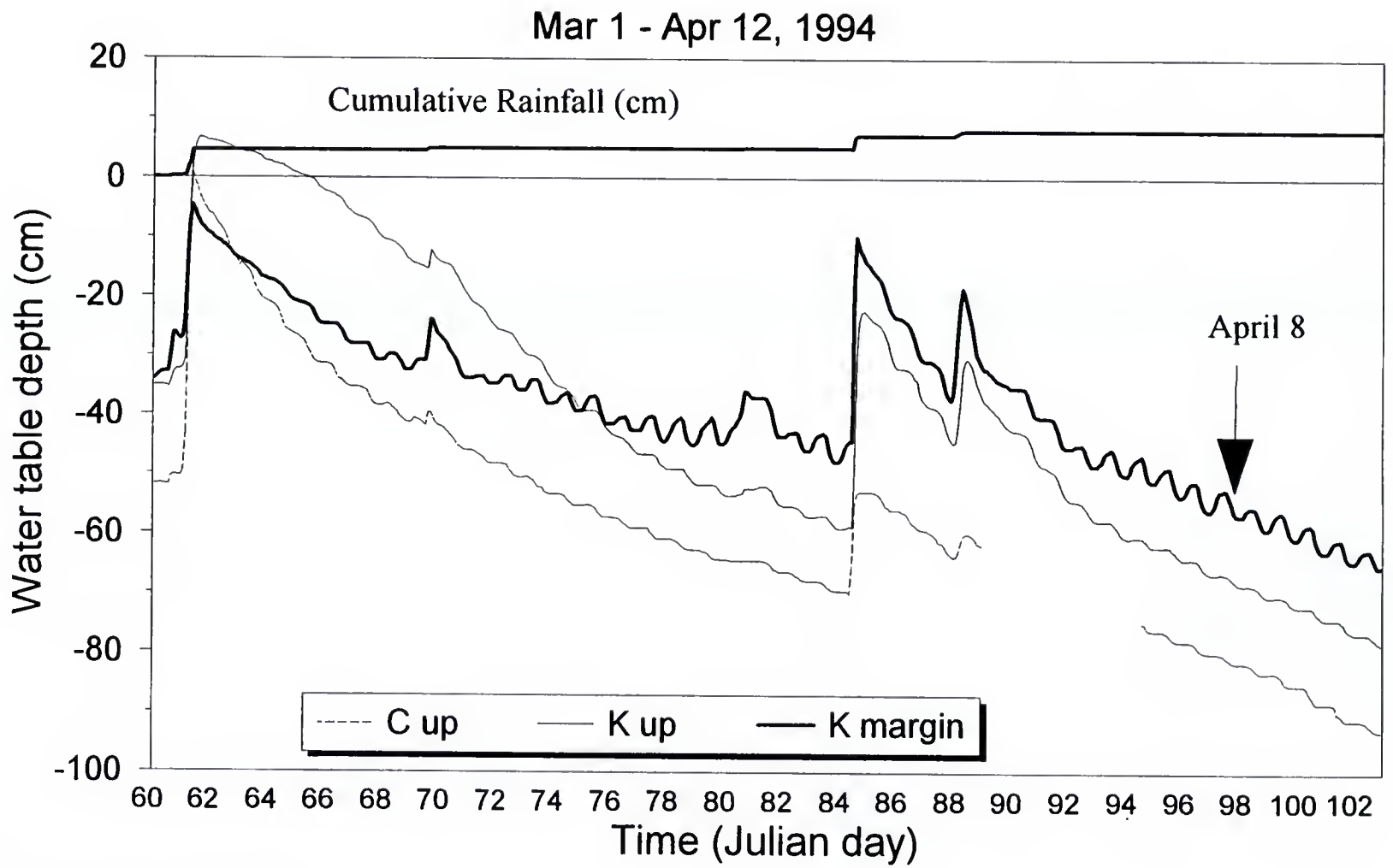


Figure 4.23 (continued)

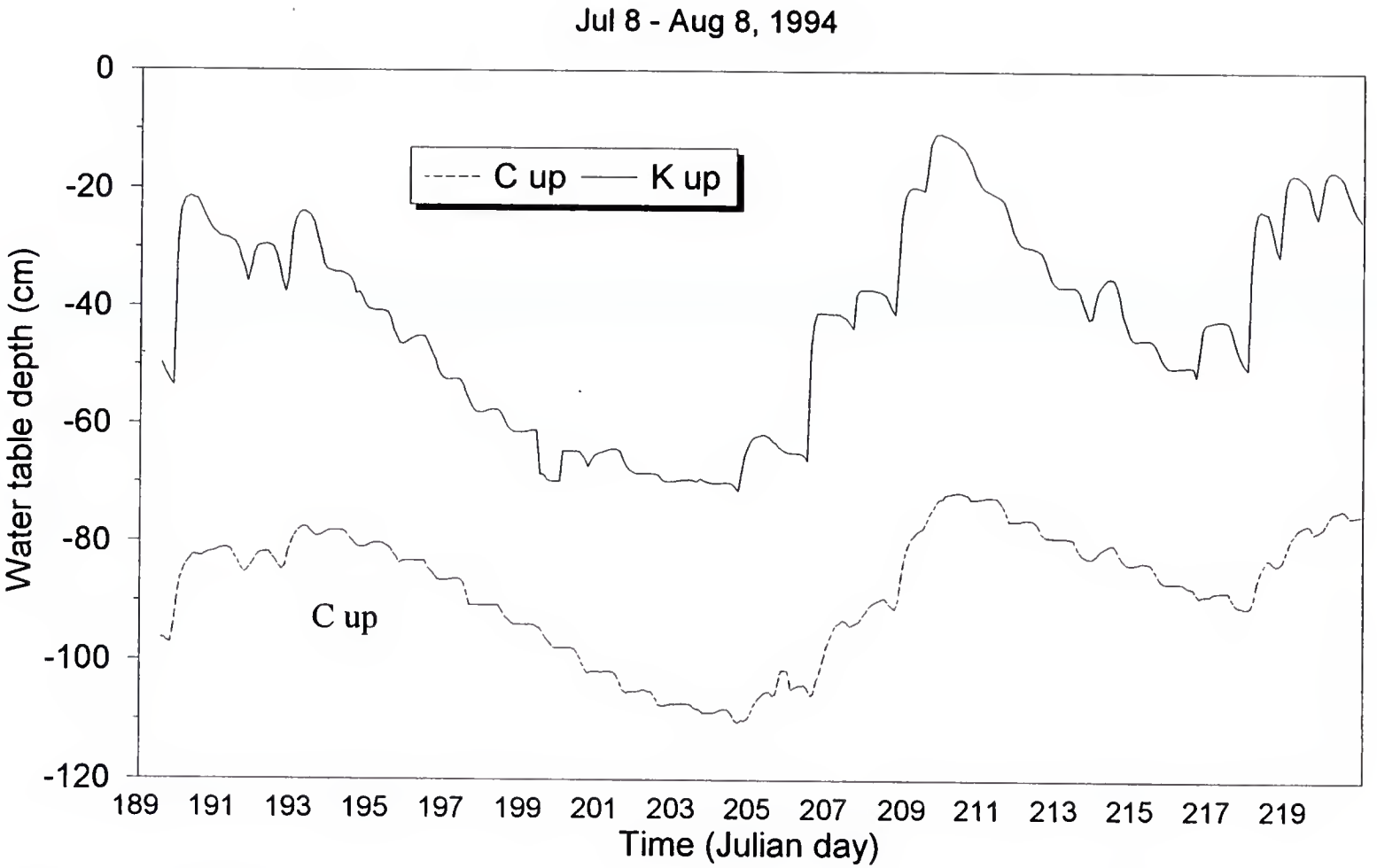


Figure 4.23 (continued)

was present during those storm events. The K margin, K upland, and C upland wells represented three different water regimes. The K margin recording well was located 25 m south of the K pond palmetto line; also it was about 25 m north of another pond edge which was located upstream of the K wetland (Figure 3.10). Although the K upland recorder was located 50 m west from the K margin, this upland site was wetter than the C upland site. The C upland site was the driest site located about 50 m east of C wetland (Figure 3.9).

The rainfall amount (RAIN) and starting water table level (START) showed significant influence on both WRR and WTR, and were the most important factors in determining the water table response (Table 4.6). Rainfall intensity (RIT) and the antecedent soil moisture conditions denoted by rainfall index (RI) were the controlling factors for K margin site. For the drier site of C upland, both the water table rise (WTR) and the water table rise rate (WRR) were closely related to the temperature index (TI), which indicated the dryness of the soil profile. The value of initial water table depth (START) and the soil moisture content decreased with the increase of TI. These correlations suggested that the water table rise was dictated by available water storage. The significant correlation between the average daily air temperature (TEMP) and the water table rise (WTR) in uplands might reflect the initial water loss effect by evapotranspiration during storms.

To compare the average water table response in wetlands and uplands, the Ratio of Water Table Rise (RWR) in analogy to the concept of hydrologic response of stormflow (Hewlett and Hibbert, 1965), has been defined as follows:

RWR = water table rise in one storm event/total rainfall amount = WTR/RAIN

Figure 4.24 presents the seasonal variations of RWR in selected storms for different sites.

Table 4.6. Factors affecting water table response to storm events†.

	K margin		K upland		C upland	
Variable	WRR	WTR	WRR	WTR	WRR	WTR
RAIN		*	*	*		*
START		*	*	*	*	
RIT	*					
RI	*		*		*	*
TEMP				*	*	
n	42	42	30	30	23	23
R^2	0.26	0.65	0.57	0.87	0.68	0.74

†WRR, water table rise rate = total water table rise (WTR)/time to peak; cm hr^{-1};
WTR = total water table rise; cm;
RAIN = total rainfall amount in a storm, cm;
START = starting water table depth from soil surface, cm;
RIT = Rainfall intensity, cm hr^{-1};
RI = Rainfall index = total 7-day rainfall amount before the storm event;
TI = Temperature index = Average 7-day temperature before the storm event;
TEMP = air temperature, °C;
n = total number of samples;
R^2 = Regression coefficient;
* denotes the factors are significant at the 95% confidence level.

Average values of RWR for wetland, wetland margin and upland soils were determined as 9.6, 14.1 and 10.2 respectively. Duncan's test by ANOVA showed that the average RWR of both the K upland and the C upland wells were significantly lower at the 95% confidence level than that of the K margin well. It was hypothesized that two factors caused the highest response in wetland margins of wetland-upland systems: 1) Wetland margins maintained higher groundwater table levels and soil moisture content than upland soils; and 2) wetland

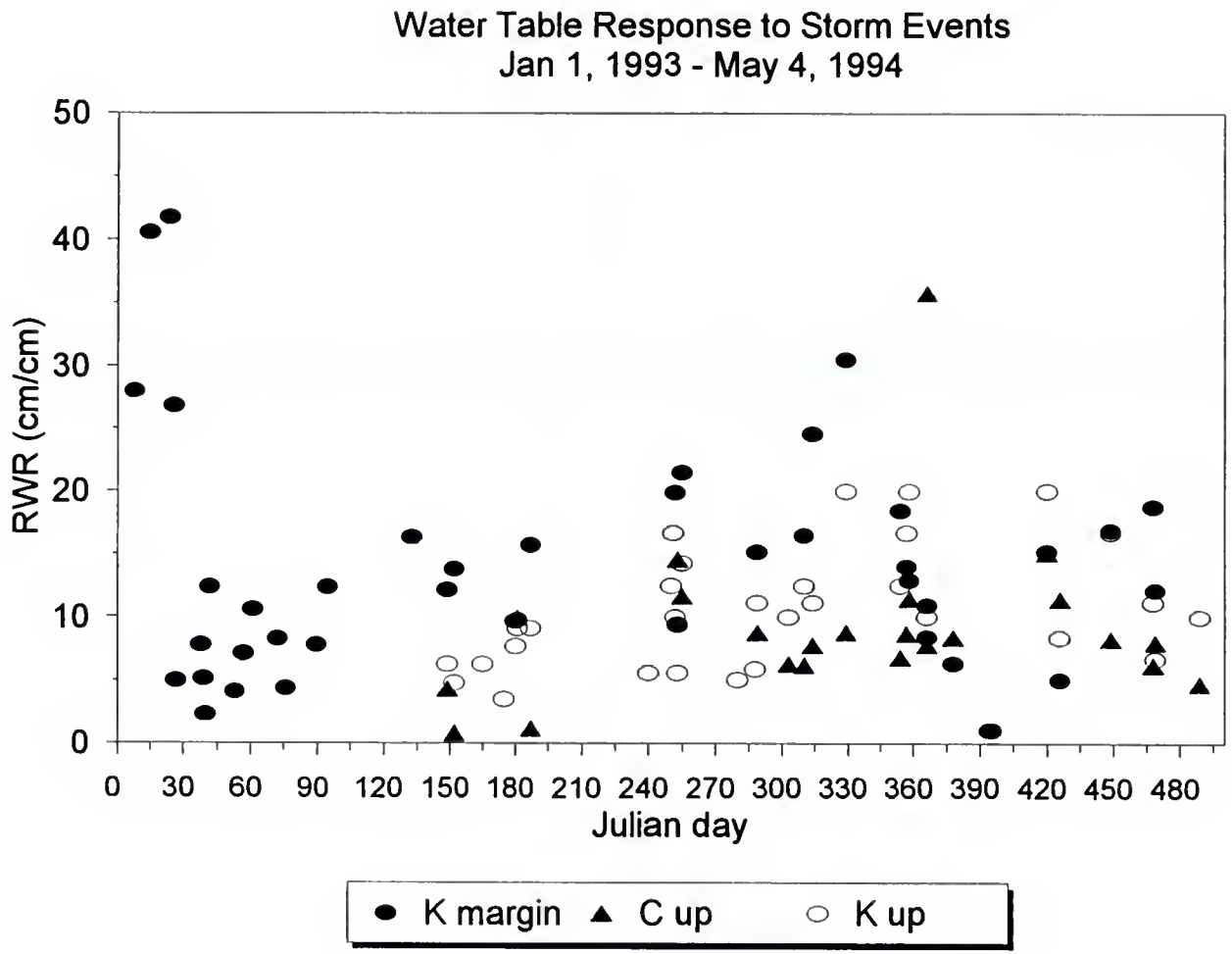


Figure 4.24. Seasonal variations of water table response (RWR) at two pine upland sites and one wetland margin site during 1993-1994.

margins had similar soil porosity to uplands, but lower soil porosity than wetland soils. Thus, wetland margin soils normally had the lowest available soil water storage and therefore the water table was more dynamic during storm events.

Specific yield. Specific yield (S_y) is the ratio of the volume of water that drains from a saturated formation owing to the attraction of gravity to the total volume of the formation (Fetter, 1988). This parameter is very important in characterizing the water table rise or decline, and is one of the most sensitive parameters in groundwater models. Assuming no soil water hysteresis this definition was given for the draining process of porous media such as soils, but S_y may also be defined as the ratio of volume of water that recharges an unsaturated soil. In a mathematical form, S_y may be expressed as:

$$S_y = \theta_s - S_r \tag{4.5}$$

where,

S_r = specific retention or the water content that a soil can retain after draining or before recharge;

θ_s = saturated water content or porosity.

Although S_y may be approximated as a constant in a porous medium for the continuity equation to model groundwater flow in an unconfined aquifer, the validity of constancy is questionable for flatwoods soils. As described in the last section, the water table fluctuated tremendously by as much as 60 cm in a single storm event. The soil porosity and soil moisture content also varied significantly in such a range in flatwoods soils. The specific yield essentially varied both in space and time. The specific yield has to be reexamined to describe adequately the groundwater dynamics in flatwoods.

Following the work by Duke (1972), Keen (1992) proposed a term, variable storativity (S_v), to substitute the traditional concept of specific yield as a better representation of the water table response. He suggested there was a significant difference between specific yield and variable storativity when the water table approached land surfaces and/or when high fluctuations occurred. Variable storativity considers the variable soil moisture content distribution above a water table as a result of the hydrologic interactions between the unsaturated zone, capillary fringe, and the saturated zone.

Flatwoods sandy soils have a low water retention capacity, and the soil moisture content in the top layer (0-20 cm) of the study area decreased rapidly following the water table drop (Figure 4.10). However, the soil moisture content in deeper layers (75 cm), varied rather slowly. As shown in the previous graphs (Figure 4.23), the water table rose dramatically and almost simultaneously with rainfall events. The water table was within the 20-cm depth for more than a month in the winter. The capillary fringe reached the soil surface during these wet periods. All those highly variable conditions may justify the use of variable storativity as a refinement of the traditional parameter of specific yield in ET analysis and groundwater modeling.

S_v can be expressed as a function of the water table depth in a similar way as Equation 4.5:

$$S_v(d) = \theta_s - \theta(d) \qquad (4.6)$$

where,

$\theta(d)$ is a function of the water table depth (d).

Combining Equation 4.6 with the previous water table-soil moisture content relations

(Equation 4.3) resulted in the general relation between S_v and water table depth for different soil layers:

$$S_v(d) = (\theta_s-\theta_{min})[1-[\frac{1}{1+(\beta(d-L))^a}]^b] \quad (4.7)$$

An average value over the range of initial water table (d_o) and the final water table (d) in one time step should be used to use the above variable storativity S_v in modeling applications, or for ET estimation from a water table hydrograph. The average, S_v, may be expressed as:

$$\overline{S_v} = \frac{\int_{z_o}^{d} S_v(z)dz}{d-z_o}$$

For example, S_v may be 0.10 for the case that a water table rises from a 50-cm depth to the ground surface. However, it may decrease to 0.05 for the case that the water table rises from a 40-cm depth.

Evaluation of water table response with a water flux balance equation. Water table fluctuations reflect the water flux balance of the water table aquifer system. Four typical water table hydrographs are presented in Figure 4.25, showing the response of the water table to storm events or ET. Water flux balance equations are derived below to quantitatively explain those four cases.

During any period, the change of water storage (dS/dt) in a soil system such as a soil column with finite volume, represents the difference of water inputs and outputs. For the

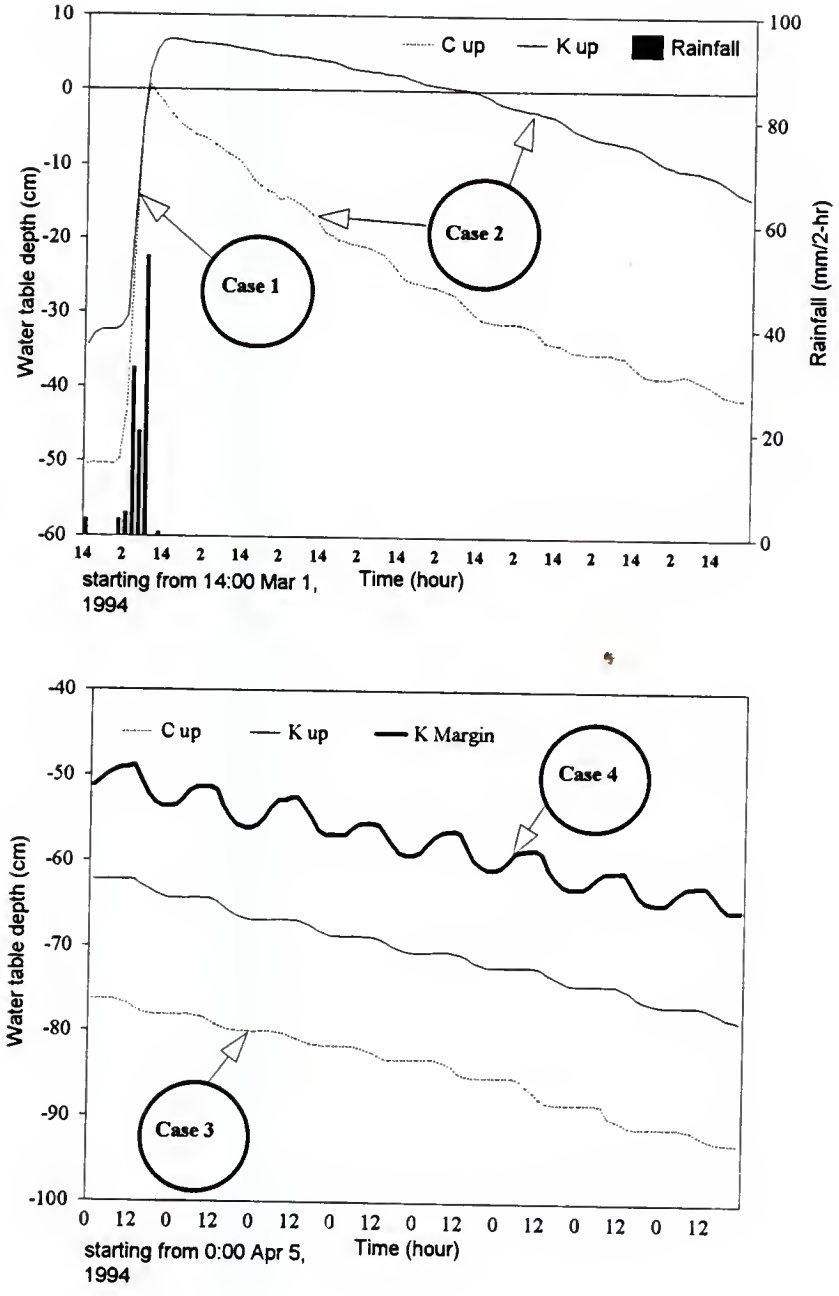


Figure 4.25. Analysis of the groundwater table fluctuation with a soil water balance method results in four major cases representing the drying-wetting cycles of flatwoods soils.

unsaturated zone of a soil profile of pine flatwoods, the change of water storage ($dS_u(t)/dt$) may be expressed as a water balance equation and neglecting lateral water flows:

$$\frac{dS_u(t)}{dt} = P_n(t)-q_d(t)-E_u(t)-T_u(t)+F_u(t) \tag{4.8}$$

where,

$S_u = L_u\theta$ = water storage in the unsaturated zone (L);

L_u = the length of the unsaturated zone (L);

θ = volumetric soil moisture content (%);

$P_n(t)$ = net rainfall, the difference of rainfall and the canopy interception (LT^{-1});

q_d = drainage from the unsaturated zone (LT^{-1}), positive downward;

E_u = evaporation from the soil surface of the unsaturated zone (LT^{-1});

T_u = water flux that is extracted by plant roots and lost through transpiration (LT^{-1});

F_u = water flux from the saturated zone to the unsaturated zone (LT^{-1}).

Similarly, for the saturated zone, the change of water storage ($dS_s(t)/dt$) can be expressed as:

$$\frac{dS_s}{dt} = \frac{dW_T(t)/dt}{S_y(d)} = q_d(t) + q_g(t) - T_s(t) - F_u(t) - q_l(t) \tag{4.9}$$

where,

$S_s(t)$ = water storage in the saturated zone (L);

W_T = water table elevation (L);

q_d = drainage from the unsaturated zone (LT^{-1}), positive downward;

T_s = transpiration from the saturated zone (LT^{-1});

q_g = net groundwater flow (LT^{-1}); positive if inflow > outflow;

q_l = deep seepage through the bottom of the saturated zone (LT^{-1});

F_u = water flux from the saturated zone to the unsaturated zone (LT^{-1}).

Combining (4.8) and (4.9), gives,

$$\frac{dW_T(t)}{dt} = \frac{1}{S_y(d)}[P_n(t) - \frac{d\theta}{dt}L_u - \theta\frac{dL_u}{dt} + q_g(t) - E_u(t) - T_u(t) - T_s(t) - q_l(t)] \tag{4.10}$$

Substituting the total ET with $E_T(t) = E_u(t) + T_u(t) + T_s(t)$, and the infiltration rate i(t) with $i(t) = P_n(t) - dS_u(t)/dt$, then Equation 4.10 can be rearranged as:

$$\frac{dW_T(t)}{dt} = \frac{1}{S_y(d)}[i(t) + q_g(t) - E_T(t) - q_l(t)] \tag{4.11}$$

The water table hydrograph combines the eight components of Equation 4.10. These water fluxes vary with time and space, and are difficult to quantify on a small time scale. However, by studying the water table hydrographs, some important features of the flow regime in flatwoods may be revealed. Fourteen large storm events, which had 50-130 mm rainfall in a 24-hour period during May 1993 - August 1994, were recorded. Hydrographs (Figure 4.23) with a 2-hour interval for the K upland, K margin and C upland sites were analyzed with the water flux balance equation 4.10. The water table fluctuation patterns in flatwoods soils were summarized in four cases (Figure 4.25) as described below.

Case #1. The water table rise was rapid and occurred simultaneously with the rainfall input. This case was most significant for high rainfall events and/or high water table conditions (see events on Julian day 301 in 1993 and Julian days 29, 55, 61, 84 in 1994, Figure 4.23). During heavy storms, the term P_n dominated the right-hand side of Equation

4.10 and caused a rapid water table rise. Under high water table conditions, normally in the winter and early spring seasons, the soil moisture content was high. Thus, the water table rise was also very significant even during moderate storm events because both the change in water storage ($d\theta/dt$) and the thickness of the unsaturated zone (L_u) were small. In contrast, when the water table was deep and soil moisture content was low in the dry seasons (spring and summer), the term $-d\theta/dt \times L_u - dL_u/dt \times \theta$ dominated the right hand side of Equation 4.10, resulting in small changes in the water table. Such cases were found on events of Julian day 149, 1993 and Julian day 190, 1994 (Figure 4.23). In fact, the water table was below the 100-cm depth and did not respond to the 44-mm storm on Julian day 240 (August 28), 1993 (Figure 4.23).

Case #2. Lateral subsurface flow was most significant when the water table was close to the soil surface and immediately after storm events. Lateral water flows represented by the net groundwater flux, q_g, may be roughly estimated by comparing the daily changes of the declining slopes of a water table hydrograph. During nights, ET(t) and i(t) in Equation 4.11 were presumably negligible. The component of the groundwater deep seepage, q_l (t), was also small and will be discussed later. So, the rapid drop of the water table was mainly caused by the local net loss of groundwater. The *Lisse effect* or the degassing processes might also play a role. The lateral water movement under high water table conditions (< 40 cm in depth) suggested a high potential of solute transport during the wet seasons. Storm events could have generated larger hydraulic gradients locally, which might last for three days. This case can be found in the after-storm parts of the hydrographs during the spring and winter months in 1994 (Figure 4.23).

Case #3. Groundwater deep seepage from the upland surficial aquifer was limited. As discussed in Case #2, $E_T(t)$ and I(t) in Equation 4.11 were negligible during nights and rainless periods; so the flat slope ($dW_T(t)/dt = 0$) of the water table hydrograph suggested that the groundwater deep seepage flux q_l was limited. This case was most significant for the C upland site, as the water table in the K upland showed more complicated patterns in the summer of 1993. The continuous decline of the water table in the K upland well at night suggested the increase of soil moisture content (positive $d\theta/dt$) in the unsaturated zone and/or continuous evaporation if not transpiration during summer nights. The possible increase of soil moisture content in the unsaturated zone was caused by the upward water movement driven by the total potential gradient. Another possible reason for this continuous decline may be the smaller soil porosity and S_v in the deep soil layers, which were more than 75 cm deep.

Case #4. Lateral groundwater recharge by the surface water was significant in the vicinity of wetlands. The water table in the K margin well which was located 25 m from the palmetto line, showed a significant rise during rainless nights in the spring seasons. This water table increase ($dW_T/dt > 0$) could only be explained by the net positive change of groundwater flux (q_g). The influx source was the pond surface water which had a higher elevation than the groundwater table in the upland. The water table in the K margin well did not show this recharge pattern other than during the spring months in 1993. The wells located at other sites did not show such water table rise patterns during rainless nights.

The water table profiles of April 8, 1994 in both the West-East and North-South cross sections in the K wetland were constructed to demonstrate the relative water table positions

in the wetland and its surroundings (Figure 4.26). The overall lower water table gradient (0.7%) and longer distance (50 m) from the wetland margin of the upland well as compared to the margin well with a water table gradient of 1.2% and 25 m from the pond edge, might explain the lower water table rise in the upland well. It was expected that the surface water - groundwater interaction in the pond margin areas was most intensive during the spring season when the difference between the pond water level and the groundwater table in the upland was the largest.

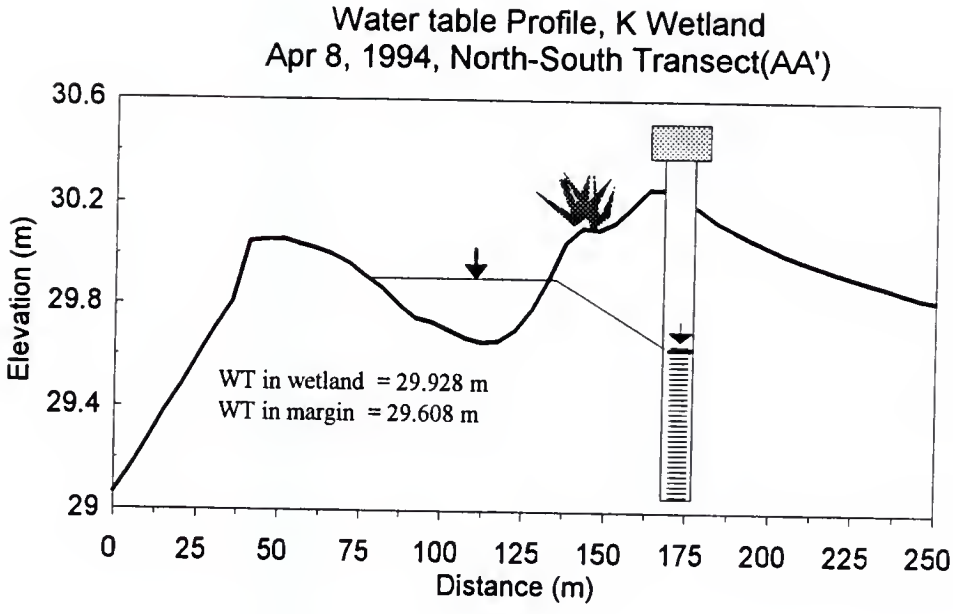
A frequently asked question about hydrologic functions of wetlands is how far away the surface water has an effect on the hydrology of the upland. This question is relevant to the following issues:

1) The surface water recharge elevates the soil moisture content in the surrounding area, and thus is beneficial to wetland margin and upland vegetation.

2) More 'irrigated areas' increase evapotranspiration loss from wetlands and the entire pine flatwoods system.

3) Contaminants moving with wetlands surface water to surrounding subsurface soils may alleviate environmental problems in wetlands.

After surface water is recharged to the surrounding groundwater system, it might continue to move following the hydraulic gradients, and the distance that the recharged water can travel is large. However, most of the slowly moving recharged water would be lost by ET along the way, especially in the summer. The higher the ET is, the shorter the affected distance. Other factors affecting this critical distance include topographical gradients, the slope of the restricting layer of the recharge areas, and the soil hydraulic conductivity.



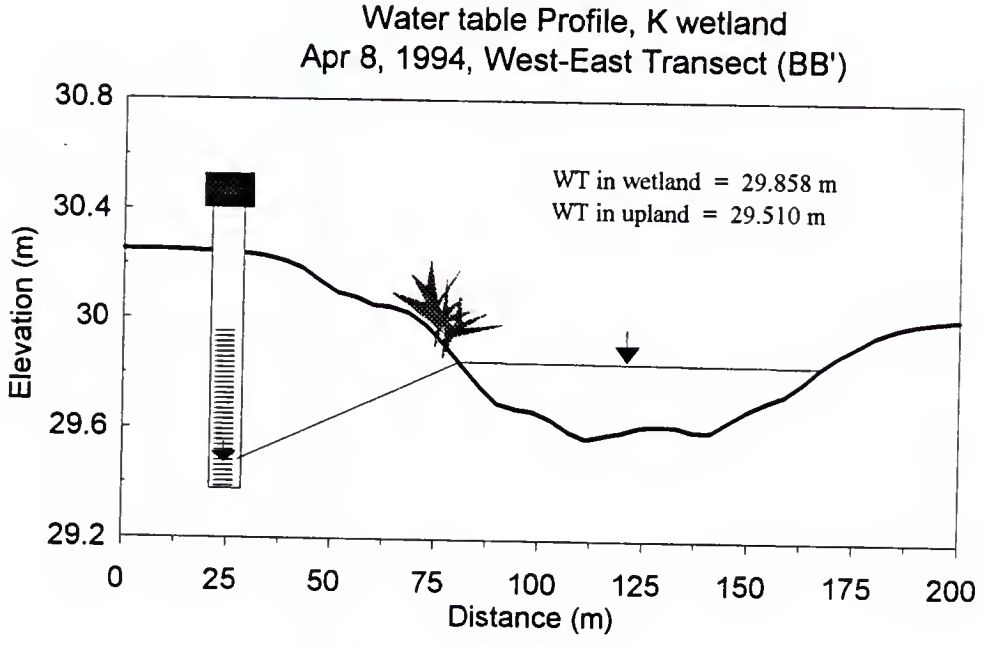


Figure 4.26. Two water table profiles in the K wetland to show the groundwater recharge induced by reversed hydraulic gradients during the spring wet-dry transition season (refer to Figures 3.10, 4.23 and 4.25).

Groundwater Flow

Groundwater flow, in both the lateral and the vertical directions, has been regarded as one of the important routes for matter and energy transfer, linking the wetlands with uplands or aquatic systems with terrestrial systems along with the overland flow and other transfer mechanisms such as litterfall (Walters and Bengtsson, 1994). Because of the high permeability and low cation exchange capacity (CEC) of sandy flatwoods soils, solutes, even normally assumed with low mobility such as P, may become highly soluble (Tremwel, 1992). So, contamination problems by the uses of fertilizers or pesticides may be more pronounced for both on-site and off-site effects in flatwoods systems. In this section, the ground water flow direction and velocity will be discussed with an emphasis upon implications for solute transport in wetland-upland systems.

Groundwater Flow Direction

Selected water table maps constructed from weekly measurements of the three systems are presented in Figure 4.28 through Figure 4.30 to represent a wet and a dry condition from May 1993 to April 1994. Water table maps in other months are presented in Appendix A. Water flow directions are denoted by the arrows perpendicular to the water table contour lines and the relative magnitude of water flow gradients are shown by the length of the arrows. Topographic maps with the same 10-cm contour interval have been given in Figure 4.27 as a reference.

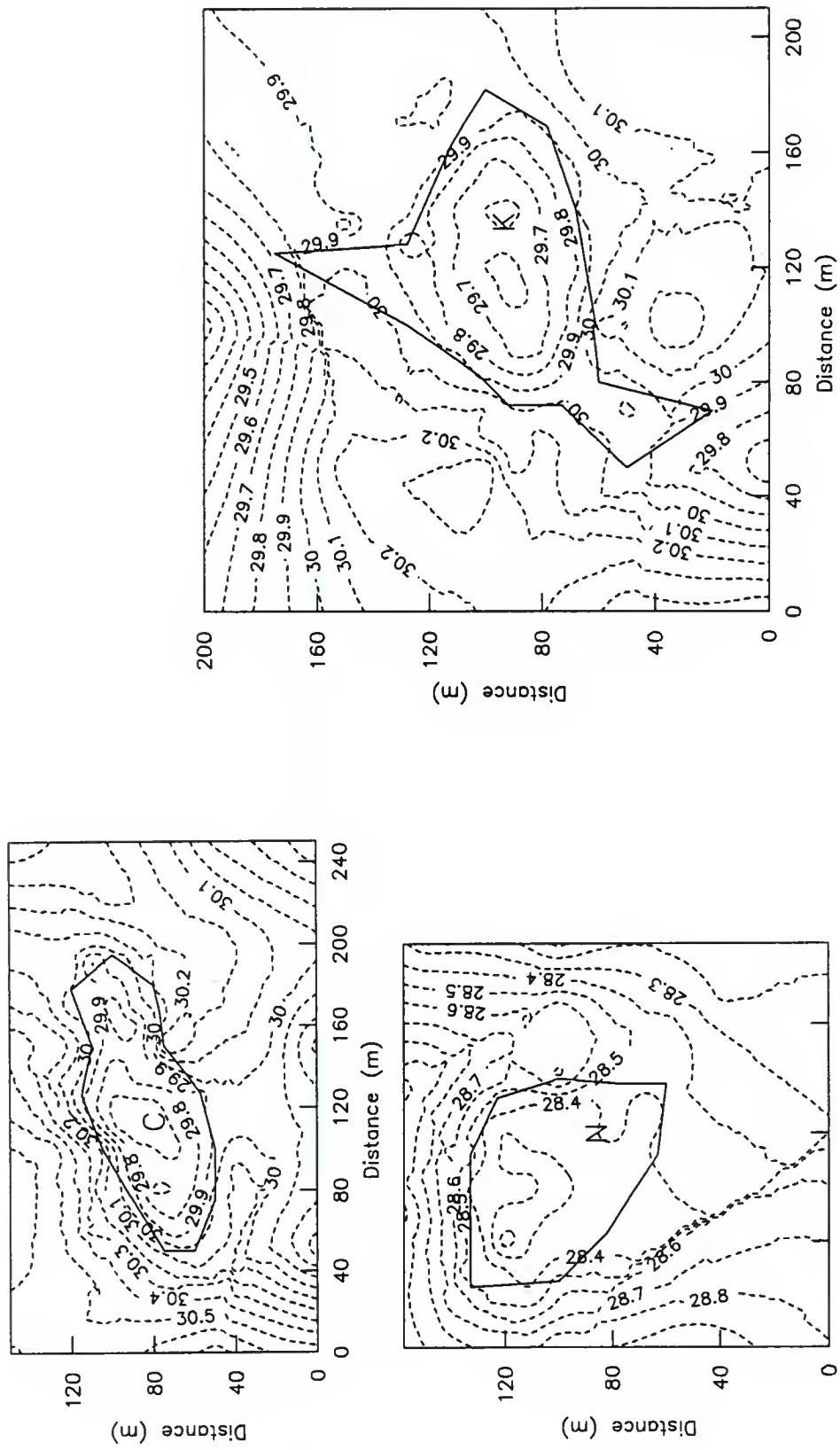


Figure 4.27. Topographic maps for the C, K, and N wetland/upland systems with the same contour interval of 10 cm as the groundwater table maps in Figures 4.28, 4.29, and 4.30.

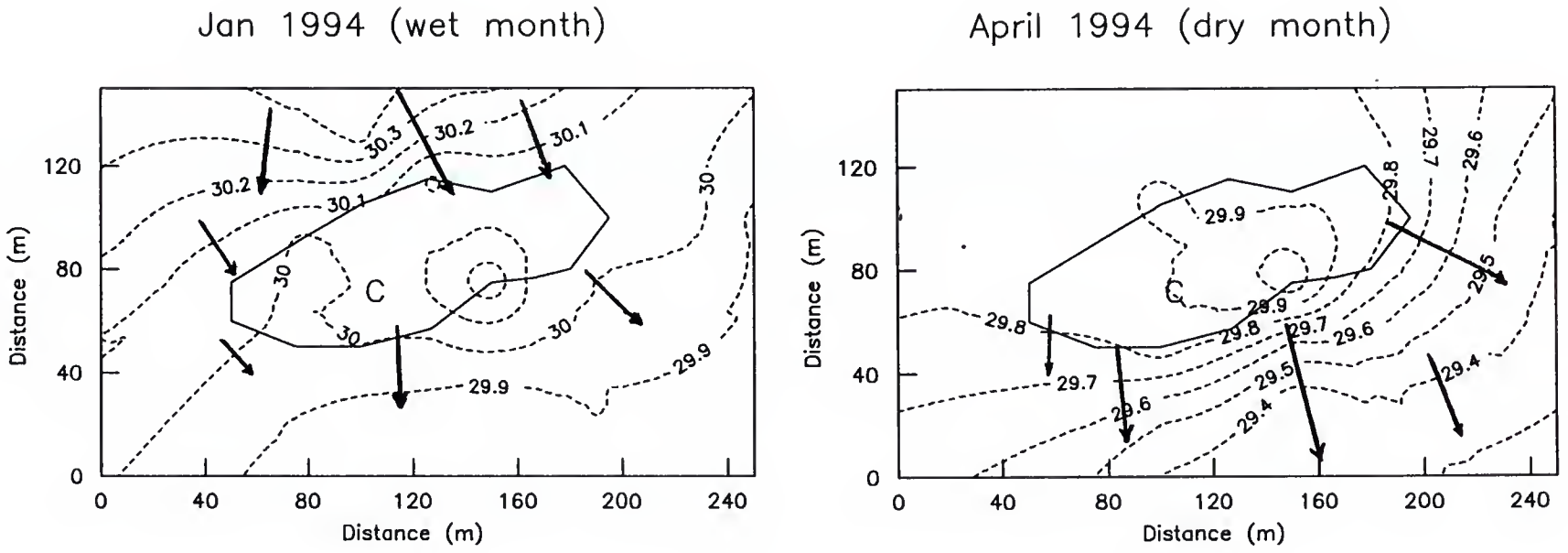


Figure 4.28. Water table maps for the C wetland/upland system constructed from weekly measurements to contrast water flow directions in a wet month and a dry month.

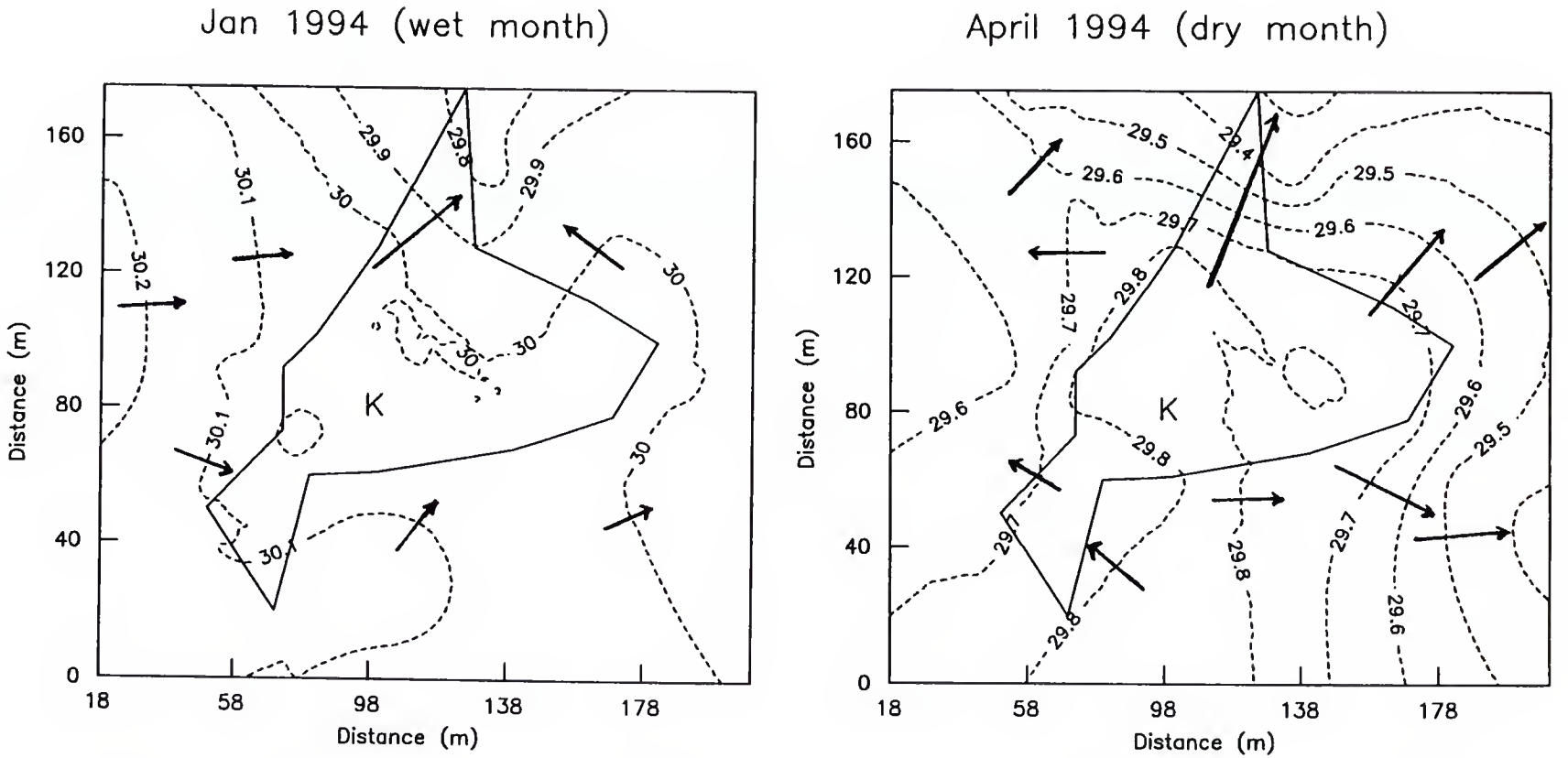


Figure 4.29. Water table maps for the K wetland/upland system constructed from weekly measurements to contrast water flow directions in a wet month and a dry month.

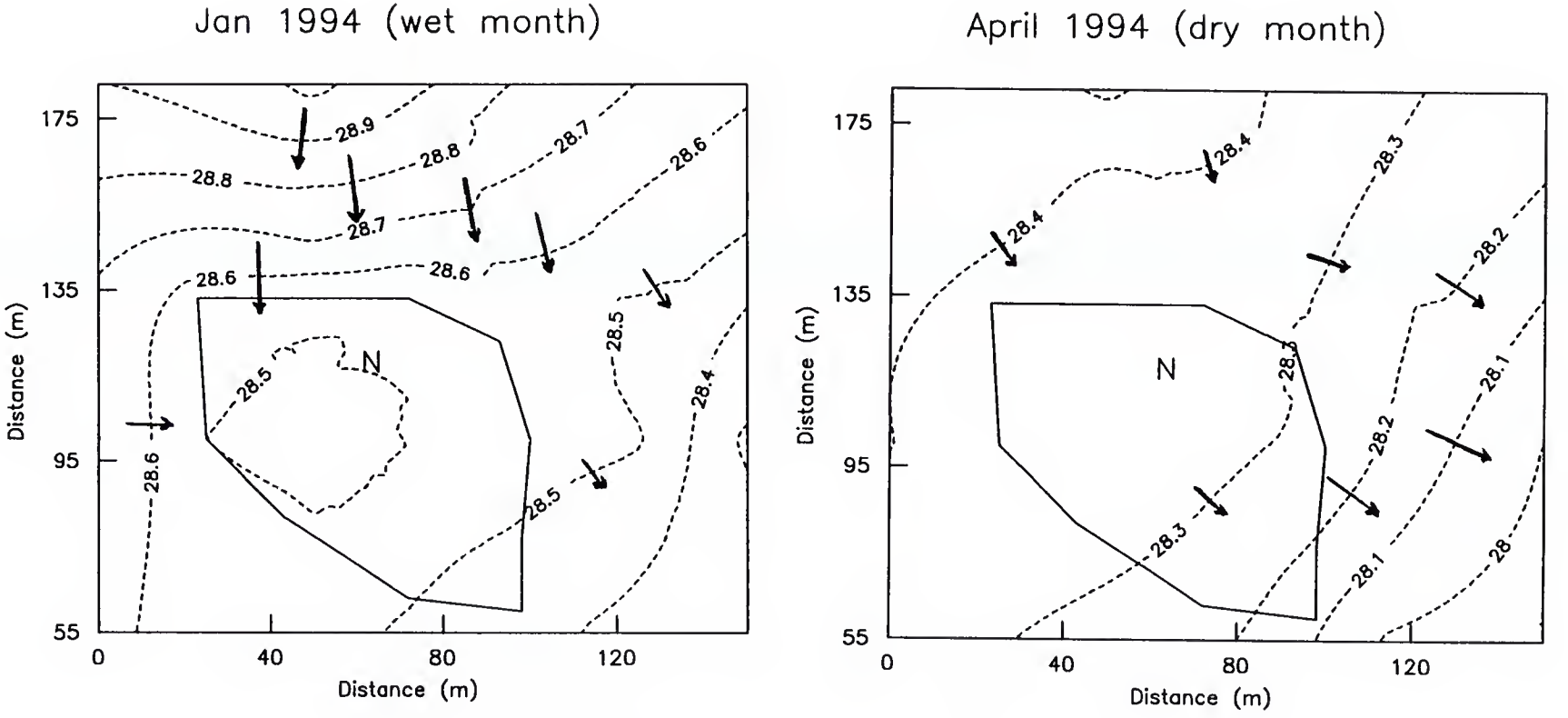


Figure 4.30. Water table maps for the N wetland/upland system constructed from weekly measurements to contrast water flow directions in a wet month and a dry month.

Water table maps for the K wetland show that the water flow direction followed the general topographic gradients, i.e., in the southwest to north direction during May 1993 - February 1994. However, the water table in the southwest portion of the upland dropped relatively faster than in the north portion and eventually the wetland became a potentiometric high in the spring transition season during March-April 1994. The water flow changed from flow-through to outflow patterns during this period. Groundwater flow directions for both the C pond and N pond followed the general surface elevation gradients and showed flow-through patterns in all seasons. The outflow gradients appeared to increase in the spring transition season of April 1994.

Crownover et al. (1995) summarized water flow patterns of 10 wetlands including K, C, and N wetlands at the research site from 26 measurements made during 1992 - 1993 (Table 4.7). The present study supports the conclusion from this large-scale study that the flow-through type was the norm with a few exceptions in measurement periods and locations. When the water table in uplands was close to the soil surface, flow-through and inflow patterns dominated the relations between wetlands and uplands. When the water table dropped from a high to a low, the flow direction showed the tendency to change from a flow-through or inflow pattern to an outflow pattern.

Groundwater Flow Velocity

Wetlands contamination by potential pollutant movement from upland forests to wetlands is determined not only by water flow direction, which reflects the sources, but also by the groundwater flow velocity, which governs the interaction time between solutes andthe

Table 4.7. A listing of 10 wetlands and the interpreted conditions of water flow between the wetland and the surrounding pine plantations.

	Number of the specific condition identified		
Wetland ID	Flow-through	Inflow	Outflow
2	26	0	0
5 (K wetland)	7	0	19
9	17	0	9
11 (C wetland)	24	0	2
28	20	0	6
21/24 (N wetland)	18	1	7
23	25	0	1
25	26	0	0
36	10	0	16
20	19	4	3

soil matrices. The average linear velocity of a solute front (V_s) in groundwater may be approximated in Equation 4.12 by ignoring dispersion and diffusion processes of the solute transport:

$$V_s = \frac{V_w}{nf} = \frac{-K_s \frac{dh}{dl}}{nf} \qquad (4.12)$$

Where, f is the Darcian pore factor, which is a function of hydraulic conductivity determined experimentally (Fetter, 1988). The spatial distribution of hydraulic conductivity (K_s) of the water table aquifer measured by the slug test method for the three systems has been presented

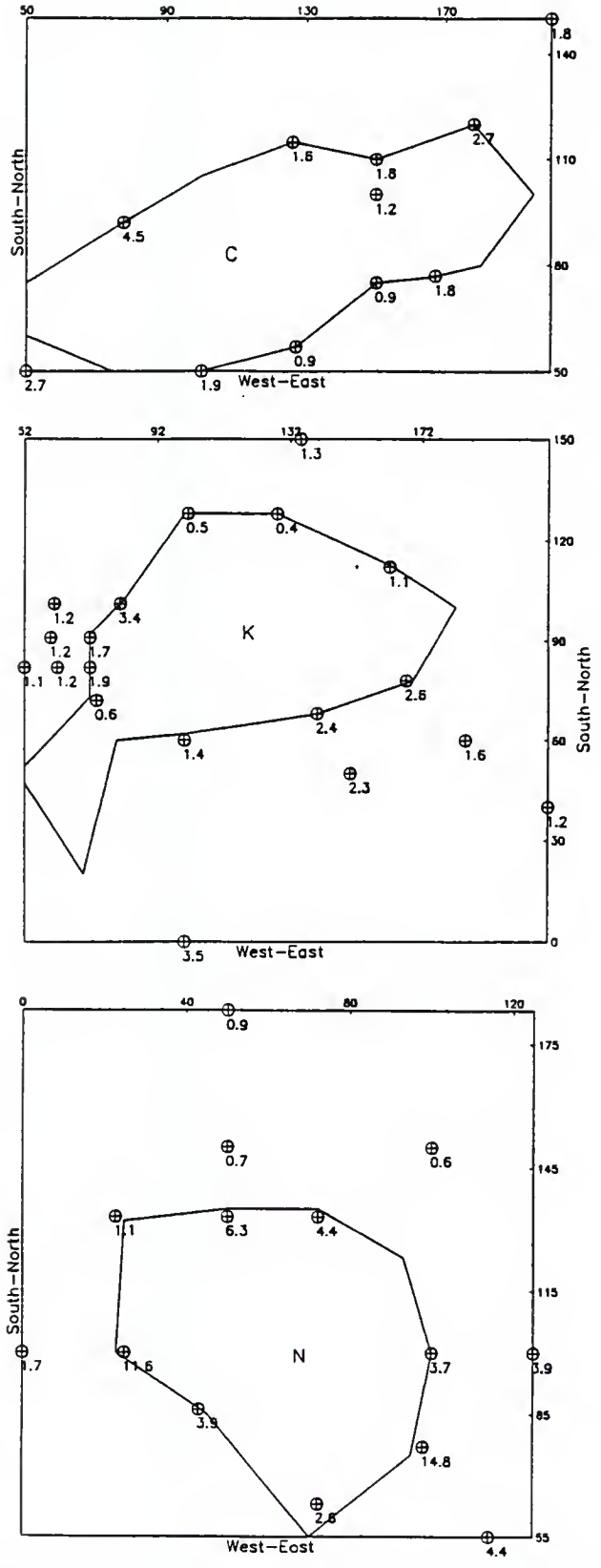


Figure 4.31. Spatial distribution of the saturated hydraulic conductivity (K_s) determined by the Bouwer and Rice method at the study sites.

Table 4.8. Saturated hydraulic conductivity of flatwoods soils †.

Wetland	C		K		N	
	K_s	WT (cm)	K_s	WT (cm)	K_s	WT (cm)
Margin	1.89	31.3	1.8	14.5	6.1	1.6
Upland	---	---	1.6	29.6	1.7	18.4
Average	---	---	1.7	22	3.9	10

† WT = water table below the soil surface at the time of measurement.
K_s = saturated hydraulic conductivity in m/day.

in Figure 4.31 and summarized in Table 4.8. The measured K_s value for each well represented the average of the whole water table aquifer depth. Since the surface layer was more porous, it was expected that K_s was higher when the water table was above the B_h horizon and close to the soil surface. Also, higher values were observed near the pond margin than in the upland soils.

Water tables of finite element #1 (FE #1) of K wetland were recorded by the three recorders located in the upland (Well 1), wetland margin (Well 2) and wetland (Well 3) (Figure 4.32). Groundwater table data for other elements in Figure 4.32 were collected manually on a weekly basis. The groundwater flow directions and the linear velocity of the solute transport determined by the finite element method have been presented in Figure 4.33 through 4.35. Figure 4.33 shows that both water flow directions and solute transport velocity of FE #1 of K wetland have significant variation. However, in the other elements, the water flow direction demonstrates less variation while the velocity varies from near zero to 9 cm/day. Non-linear relations between the water table elevations and associated hydraulic gradients of Figure 4.36 suggest that the highest groundwater outflow velocity for the K

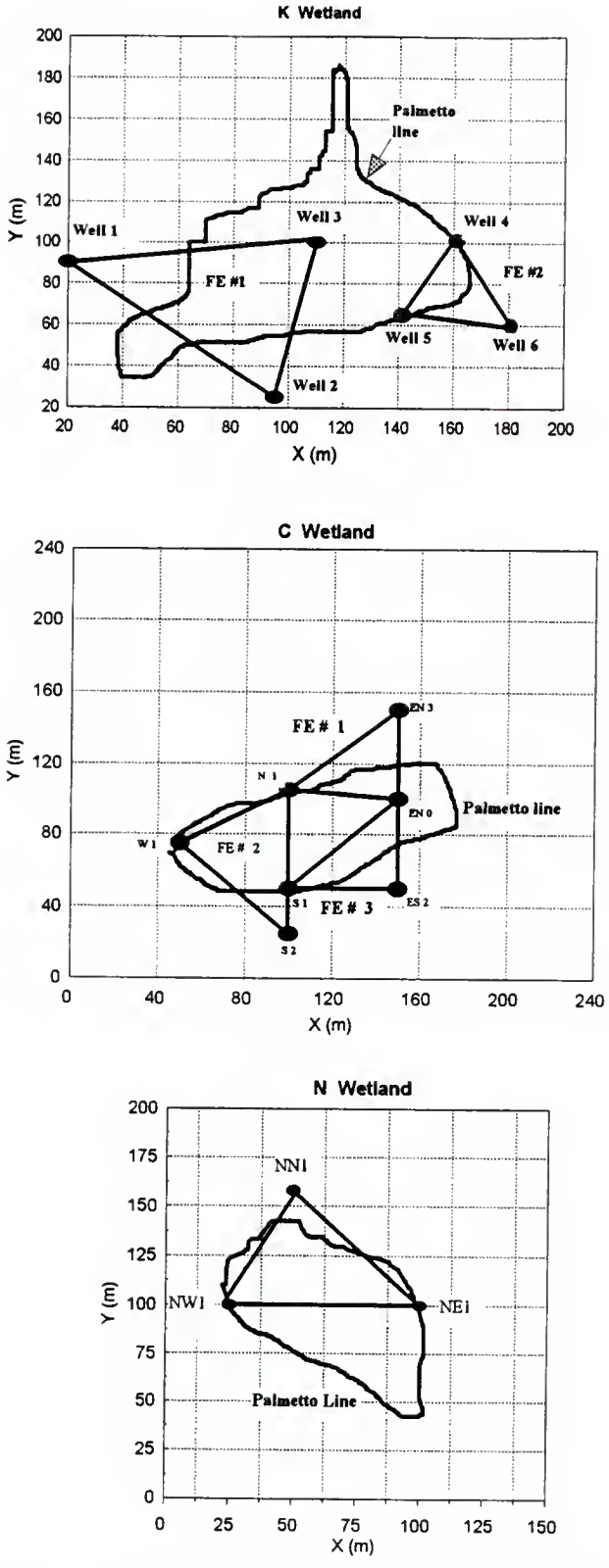
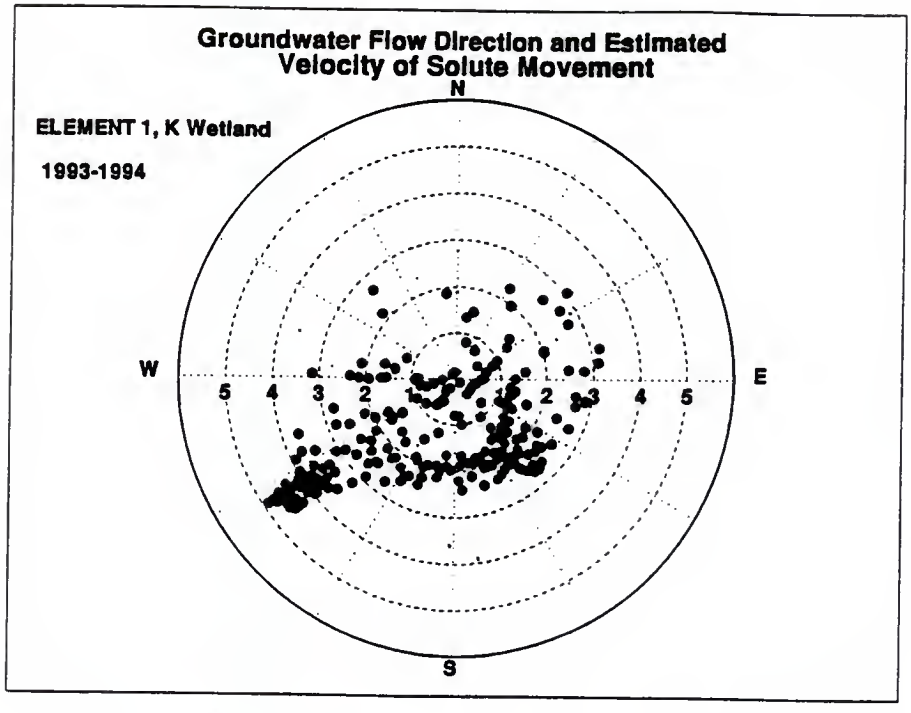


Figure 4.32. Well coordinates for the finite element analysis of groundwater flow direction and velocity.



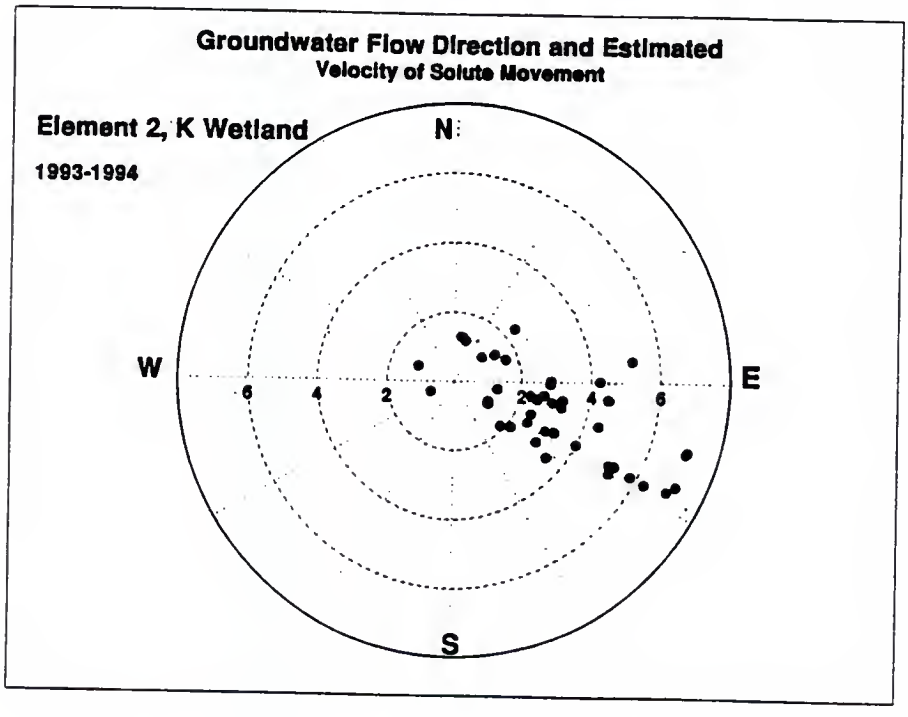
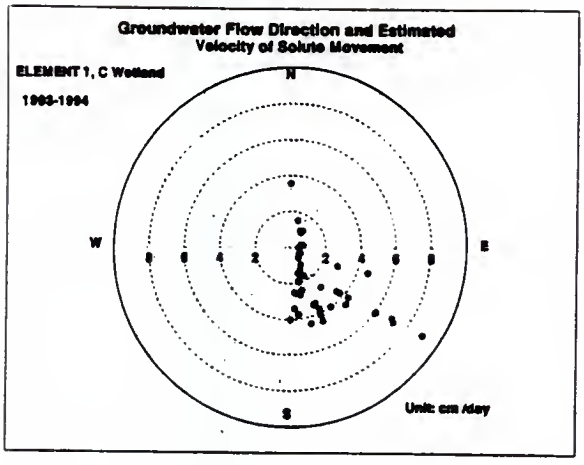
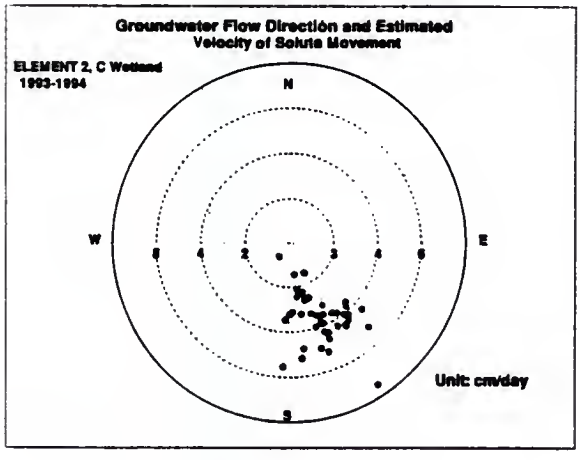


Figure 4.33. Estimated groundwater flow direction and velocity of the solute movement in two finite elements of the K wetland.





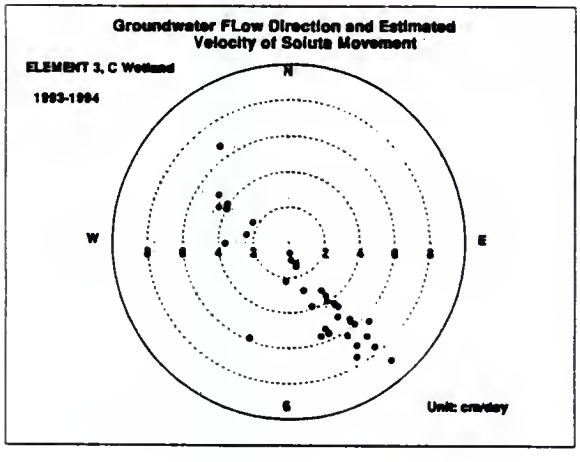


Figure 4.34. Estimated groundwater flow direction and velocity of solute movement in three finite elements of the C wetland.

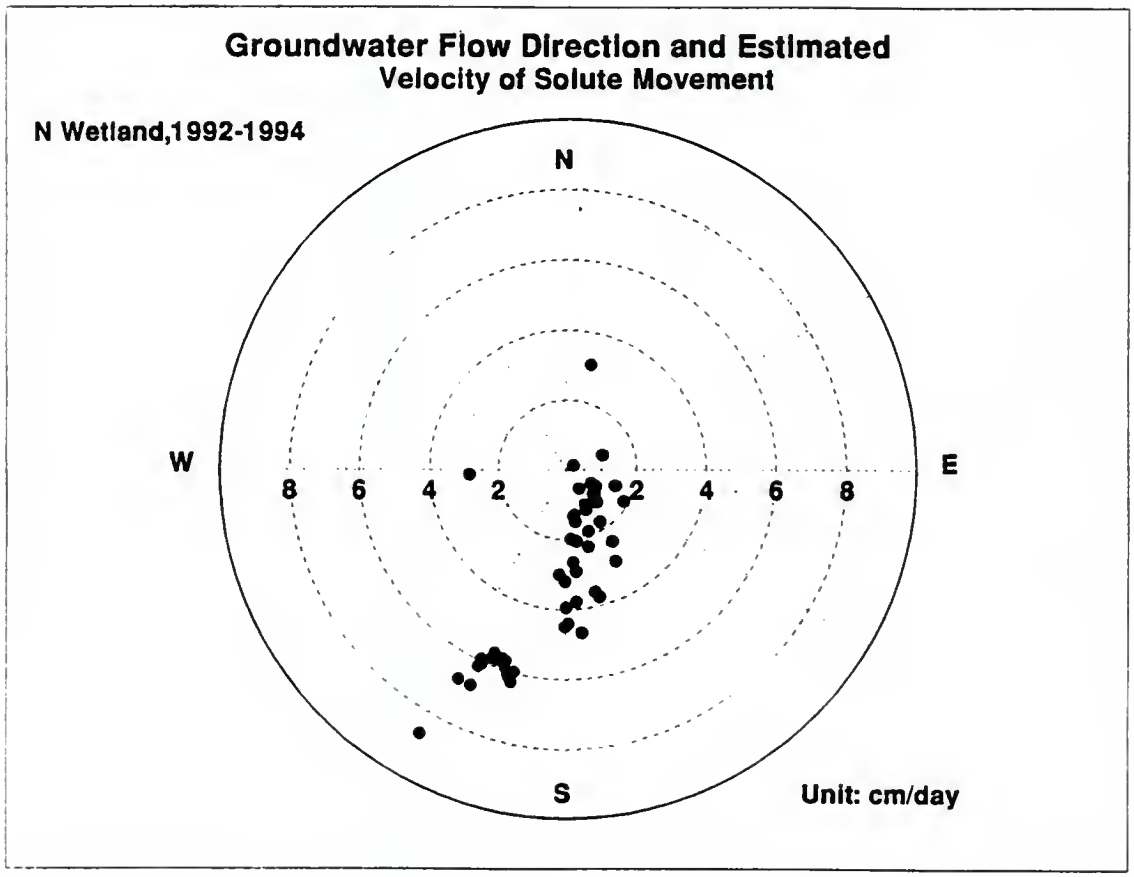


Figure 4.35. Estimated groundwater flow direction and velocity of the solute movement in a finite element of the N wetland.

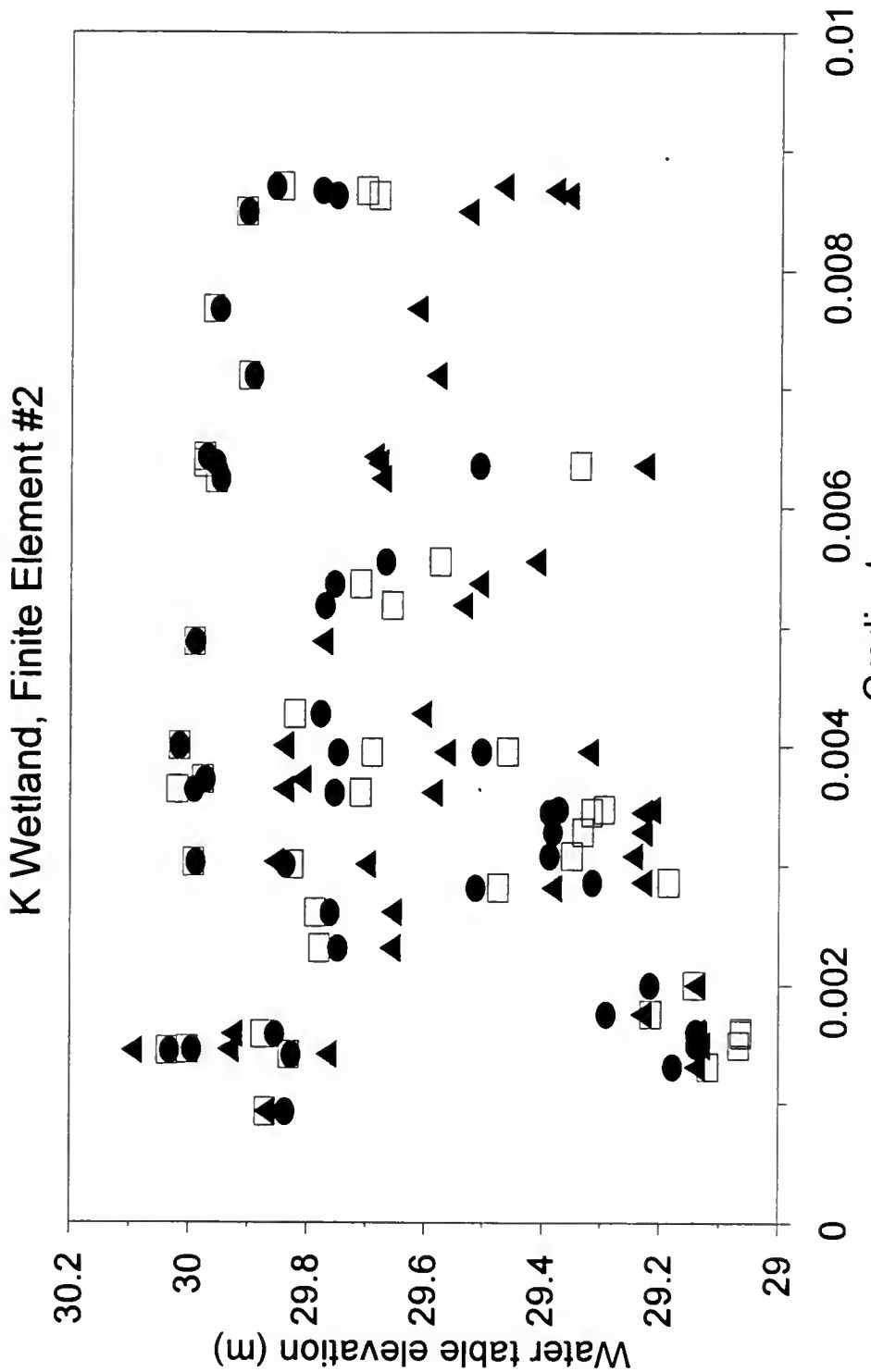


Figure 4.36. Nonlinear relationships between the hydraulic gradients and water table elevations in finite element #2, K wetland.

wetland occurred when the wetland water level was in the median rather than in the extremes. This was in sharp contrast to the C and N wetlands (Figure 4.37 and 4.38). The finite element analysis supported the conclusion that C and N wetlands were flow-through types. The relations between the water table level and its gradients are more complex in C and N wetlands than that in the K wetland (Figures 4.37 and 4.38).

The above estimated lateral velocity of the solute movement was too low to cause significant concern about contamination through subsurface flows as compared to the surface flows which will be discussed later. However, other processes such as sorption-desorption, ion-exchange, oxidation-reduction, plant uptake and other chemical/biological processes are also needed to determine the fate of chemicals in groundwater and eventually predict the effects of forest management practices on water quality parameters.

Monthly groundwater flow dynamics during 1993-1994 will be presented in the water budget section later in this Chapter.

Deep Seepage

Water loss from the surficial aquifer to the secondary aquifer systems through deep seepage was estimated by Darcy's equation parameterized with field geological information. The water table variations for the two aquifer systems have been presented in Figure 4.39. Water table data of the deep wells were recorded manually once a month. Since the potentiometric surfaces of the lower aquifer were apparently at higher elevations than the bottom of the restrictive layer, the pond water in the cypress wetlands was under some artesian pressure. The potentiometric surfaces in the secondary aquifer showed similar

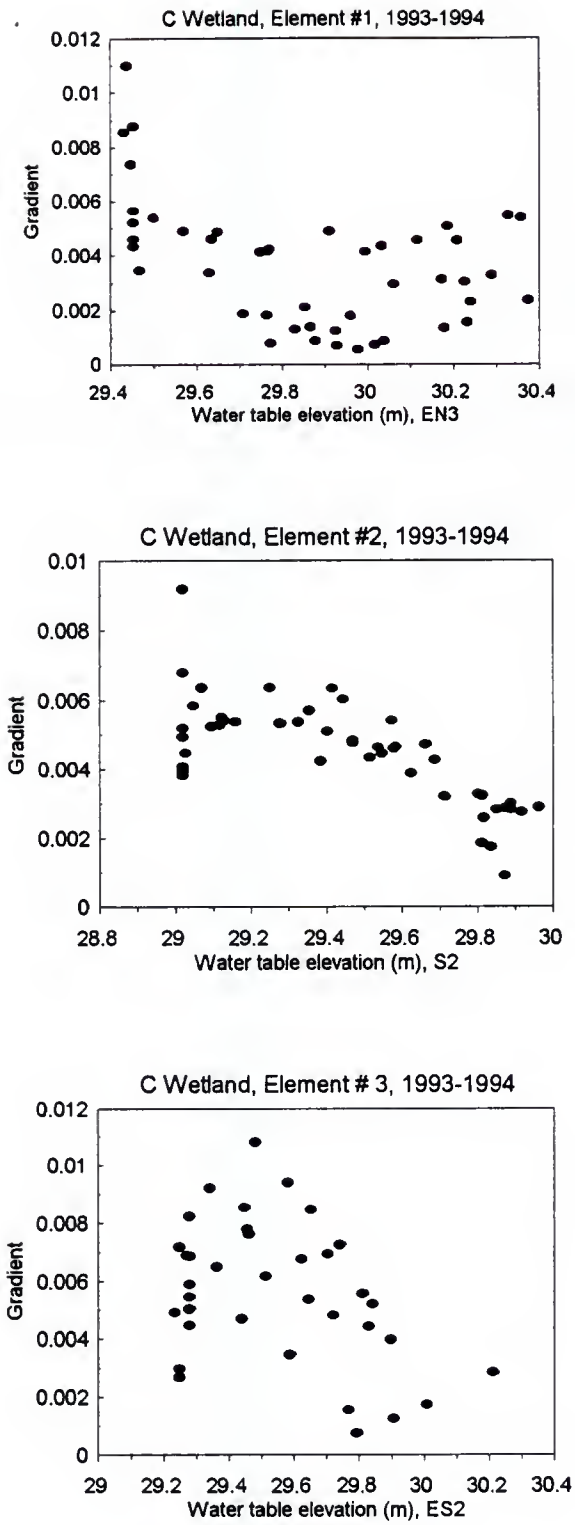
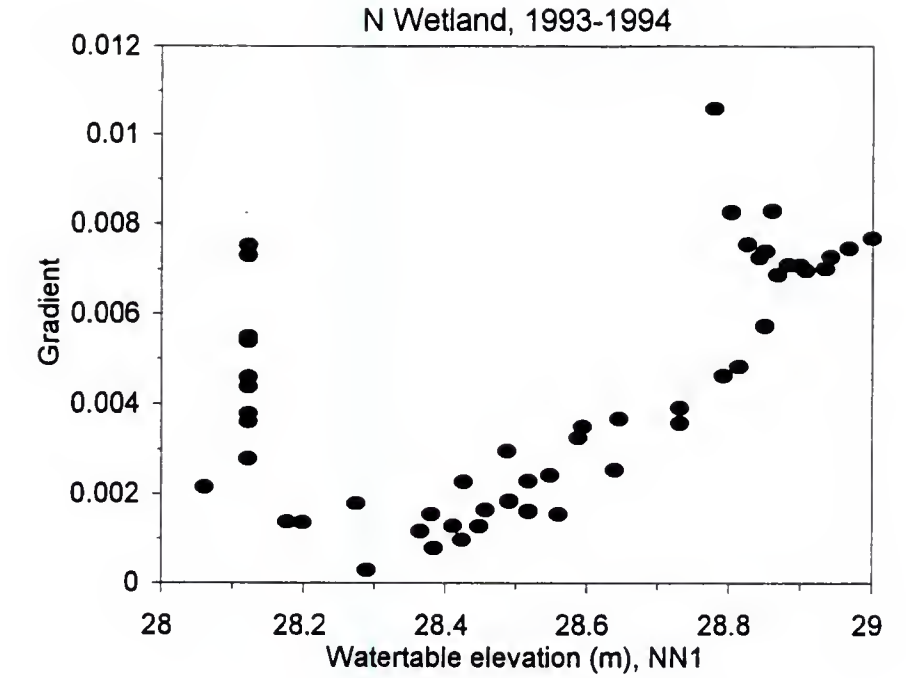


Figure 4.37. Nonlinear relationships between the hydraulic gradients and water table elevations in finite elements #1, #2, and #3, C wetland.



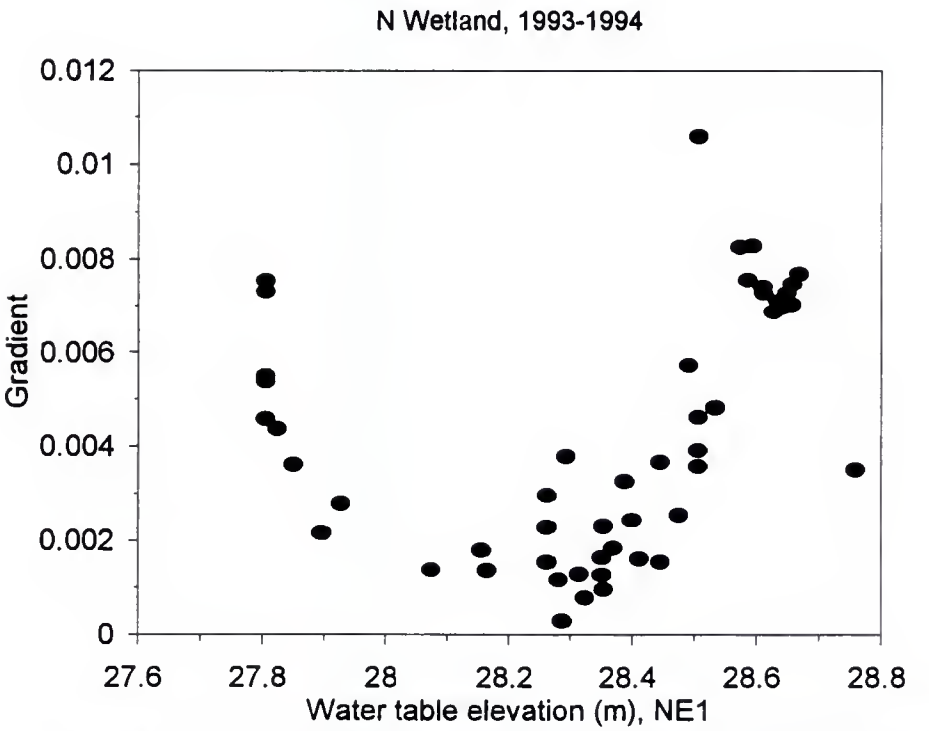


Figure 4.38. Nonlinear relationships between the hydraulic gradients and water table elevations in N wetland.

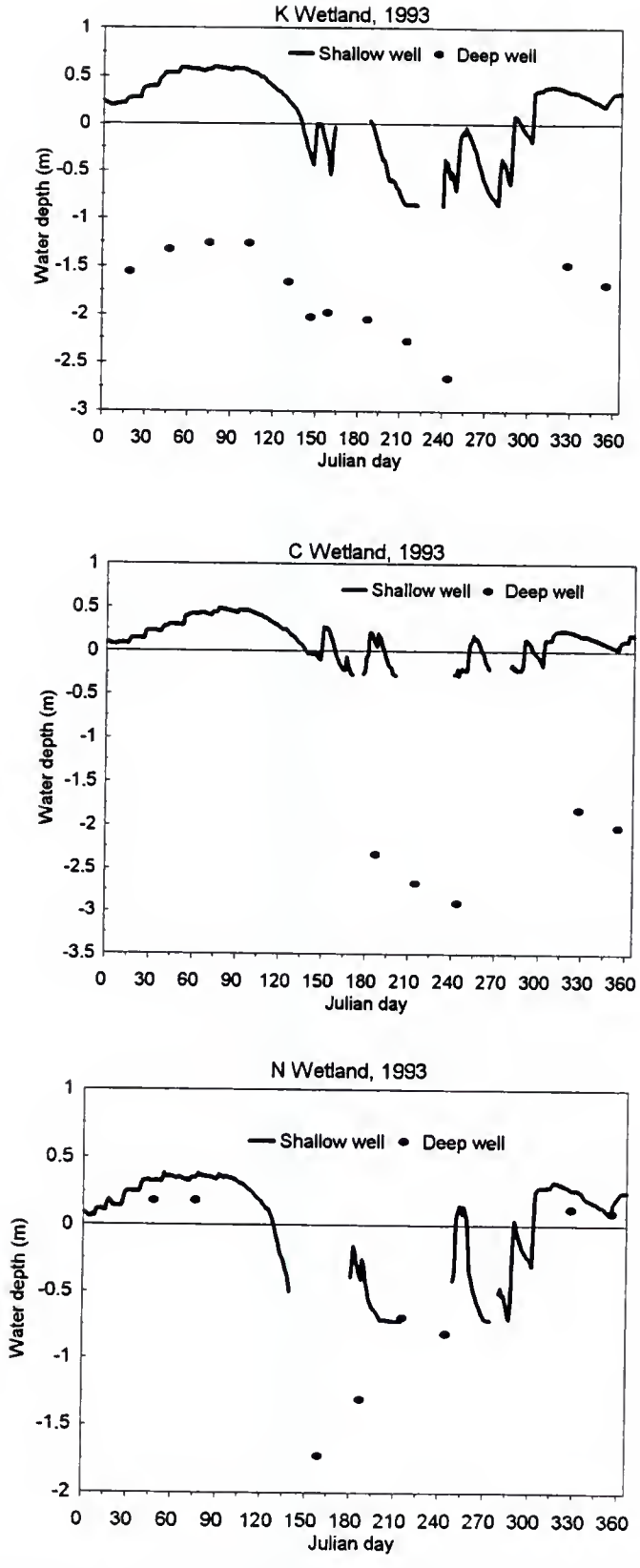


Figure 4.39. The water table variation in the deep and shallow wells in 1993.

variation patterns as in the surficial aquifer. Differences between aquifer water table levels of the N wetland were small, and sometimes a low artesian pressure existed at the pond bottom. This suggested little downward seepage loss from the N wetland. For the K and C wetlands, the casings of the deep wells were installed near the bottom of the blue clay layers

Table 4.9. Estimated deep seepage from cypress wetlands in 1993-1994.

Date of measurement	Water table depth (m)						Deep seepage (mm/day)		
	Deep well			Shallow well					
Date	K	N	C	K	N	C	K	N	C
Jan 19	-1.6	---	---	0.3	---	---	0.0	---	---
Feb 16	-1.3	0.2	---	0.5	0.32	---	0.3	0.0	---
Mar 16	-1.3	0.2	---	0.6	---	---	0.3	---	---
Apr 13	-1.3	---	---	0.6	---	---	0.3	---	---
May 11	-1.7	---	---	0.2	---	---	0.3	---	---
May 27	-2.0	---	---	-0.4	---	---	0.3	---	---
Jun 8	-2.0	-1.7	---	-0.3	---	---	0.3	---	---
Jul 6	-2.1	-1.3	-2.3	0.0	-0.4	0.1	0.3	0.3	0.0
Aug 3	-2.3	-0.7	-2.7	-0.9	-0.7	-0.3	0.3	0.1	0.5
Sep 1	-2.7	-0.8	-2.9	-0.5	-0.6	-0.3	0.2	0.0	0.5
Sep 29	-2.1	-0.5	-2.5	-0.7	-0.7	-0.3	0.4	0.0	0.6
Oct 27	-2.0	-0.3	-2.2	-0.1	-0.3	-0.1	0.2	0.0	0.5
Nov 24	-1.5	0.1	-1.8	0.4	0.3	0.2	0.3	0.0	0.5
Dec 21	-1.7	0.1	-2.0	0.2	0.1	0.1	0.3	0.0	0.4
1994 Jan 19	-1.3	0.2	-1.6	0.6	0.4	0.2	0.3	0.0	0.5
Feb 17	-1.2	0.2	-1.4	0.5	0.3	0.4	0.3	0.0	0.4
Mar 15	-1.3	0.2	-1.7	0.5	0.3	0.4	0.3	0.0	0.4
Apr 12	-1.6	0.2	-2	0.3	0.5	0.2	0.3	0.0	0.5

about 4 m deep. The differences of water table levels in the two aquifers were higher than in N pond resulting in higher hydraulic gradients. However, the deep seepage fluxes from wetlands were rather small (Table 4.9) due to the low hydraulic conductivity ($< 10^{-3}$ m/day) of the blue clay layer as suggested by Gillespie (1976).

Surface Flow

The sources of stream flow and the associated runoff generation mechanisms are important topics of modern hydrological sciences due to the implication for watershed resource management and protection (Bernier and Hewlett, 1982; Ward, 1984). For example, if the objective of a watershed is to provide maximum water yield and overland flow dominates streamflow generation of the watershed, the strategy of management practices should employ methods which reduce evapotranspiration loss and diminish depression storage on land surfaces. Protection methods should be applied throughout the watershed if soil erosion and non-point pollution by soil-adsorbed contaminants (e.g. phosphate) are of concern. In another extreme example, if storage-based runoff mechanism dominates a watershed, where storm flow originates mostly from subsurface soils and groundwater reservoirs, surface soil erosion may not be a major problem but landslide processes may be accelerated on steep slopes, and highly soluble chemical (e.g. nitrate) movement may become more pronounced. For this type of watershed, the streamside areas characteristic of variable sources have the highest priority for water quality control and the Best Management Practices may be adjusted accordingly.

Runoff mechanisms to explain the stream hydrograph may be classified into two

categories, the Hortonian overland flow theory (Horton, 1933 and 1940; Rubin and Steinhardt, 1964) and the variable source area concept (VSAC) (Hewlett and Hibbert, 1965; Kirkby and Chorley, 1967; Dunne and Black, 1970a and 1970b). The Horton theory assumes that the watershed infiltration and storage capacity decreases during a storm event and continuing rainfall intensity eventually exceeds the soil infiltration rate, and overland flow begins to emerge over the soil surface. This theory dominated the runoff process studies until the late 1960s when the variable source area concept (VSAC) emerged. The major driving forces to reexamine the Horton theory was the contradiction by observation of fast storm water responses without significant overland flow in forested watersheds (Hewlett and Helvey, 1970; Patric and Reinhart, 1971). The significant contribution of VSAC to explain storm water generation was its consideration of the spatial and temporary dynamics of soil water status and flow pathways on a watershed basis during a storm event. The VSAC may be summarized as (Hewlett and Troendle, 1975):

1. The source areas contributing to storm runoff (also called saturation area, surface water delivery drainage system) vary during a storm event; they expand faster than they contract.

2. Subsurface macropore flow through the unsaturated soil sustains the saturation area in a storm event.

3. Direct precipitation on expanding saturated areas contribute directly to stormflow increase.

The relationships between the Horton theory and the VSAC in the aspects of applicability in different environments have been presented in Figure 4.40 (Dunne, 1978).

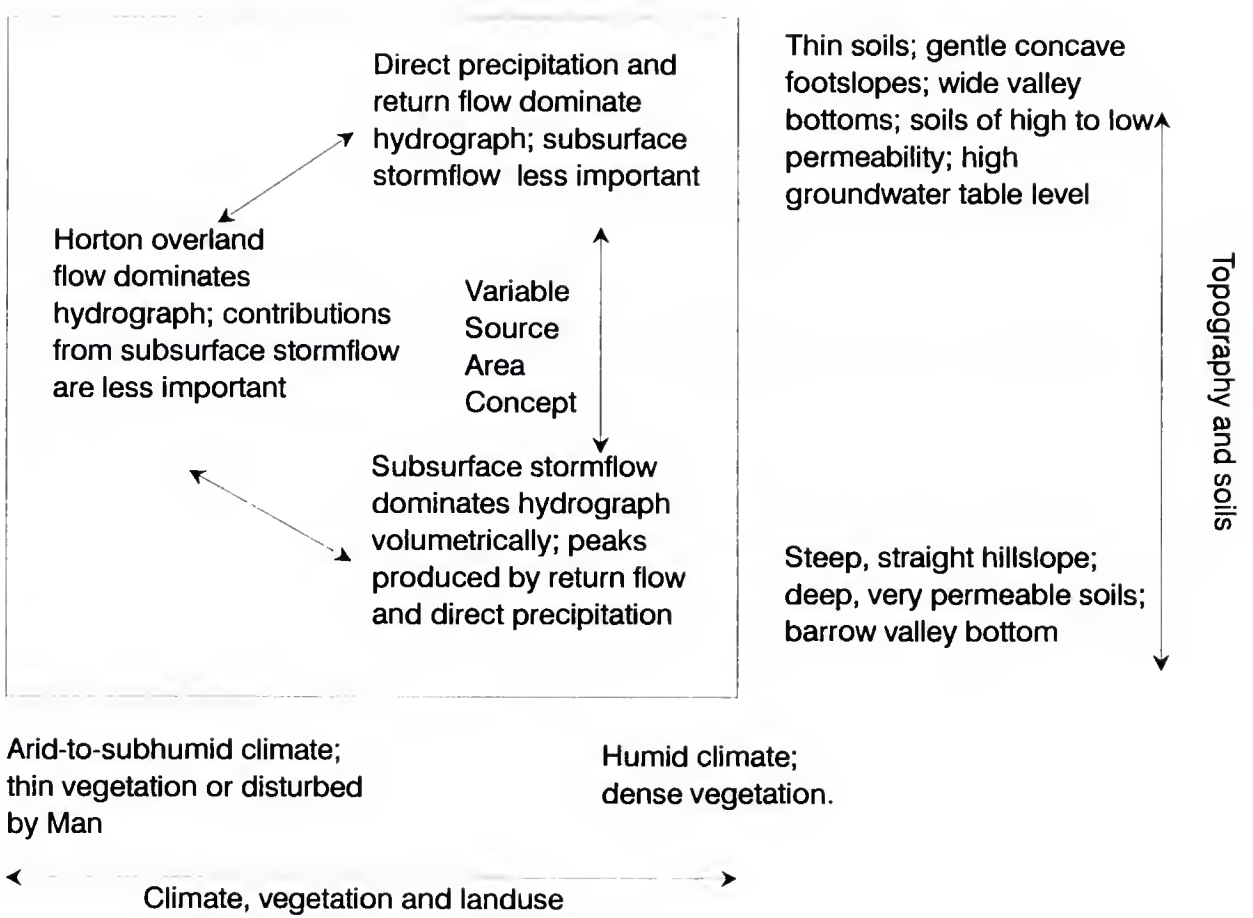

Direct precipitation and return flow dominate hydrograph; subsurface stormflow less important
Horton overland flow dominates hydrograph; contributions from subsurface stormflow are less important
Variable Source Area Concept
Subsurface stormflow dominates hydrograph volumetrically; peaks produced by return flow and direct precipitation
Thin soils; gentle concave footslopes; wide valley bottoms; soils of high to low permeability; high groundwater table level
Steep, straight hillslope; deep, very permeable soils; barrow valley bottom
Topography and soils
Arid-to-subhumid climate; thin vegetation or disturbed by Man
Humid climate; dense vegetation.
Climate, vegetation and landuse

Figure 4.40. Schematic of various runoff processes and their controls (adapted from Dunne, 1978).

It shows that Horton overland flow occurs most frequently in poorly-vegetated arid and semi-arid landscapes where soil infiltration rates are low, while the VSAC is most applicable in well-vegetated, humid climatic conditions where the infiltration capacity is high. Although the VSAC was proposed for forested watershed conditions, it is not incompatible with Hortonian methods for analyzing runoff from semi-arid basins (Arteaga and Rantz, 1973; Lane et al., 1976). The variable source area in a watershed represents areas where the groundwater table comes to the soil surface, and essentially the infiltration rate becomes zero and overland flow occurs. Similarly in an extreme case, when the Hortonian overland flow dominates the entire area of a watershed, the variable source area may be viewed as being the maximum surface area of the watershed. Thus, the VSAC may be regarded as a universal theory to explain storm flow response from a watershed in any landscape. However, for practical purposes, Hortonian models may be sufficient and more effective for prediction of the total runoff amount, especially in overland flow dominated areas (e.g., urban or mountainous areas).

The flatwoods fits in the humid climate region with extremely low topographical gradients as classified in Figure 4.40. However, few studies have been conducted on flat terrain to support the VSAC, which was developed primarily by investigations of hilly forested watersheds. In the next section, the surface runoff characteristics in the present wetland-upland systems are presented in the context of the VSAC.

Runoff Characteristics

Daily outflow dynamics of the study wetlands during 1993-1994 have been presented

in Figure 4.41. Field observations did not show any surface inflow to the C pond. However, surface inflow from ponds adjacent to the K and N ponds was significant. Surface outflow occurred during the winter and early spring seasons between January and April, when groundwater table elevations were high and the available pond water storage was depleted. In late October of 1993, following a wet month with a total rainfall of 139 mm, an 88-mm storm event occurred in a 25-hour period. The water table level in upland soils increased more than 76 cm and surface outflow was induced in the K wetland, which lasted about two weeks into November, a dry month with a total rainfall of 38 mm. Field observations showed overland flow events in forest uplands were not common during dry periods in summer time, even with big storms, due to the high infiltration rates and ET-induced storage capacity of the sandy soils. However, surface water could occur in depressions between two planting beds during wet periods because of a high water table in upland soils. Although most of the small areas of surface water normally were isolated and stagnant, those that were near wetlands were frequently connected to the main water body through either existing drainage systems around ponds or beds which were leading into wetlands.

The above analysis has shown that three factors controlled the runoff characteristics of wetland-upland flatwoods systems:

1. The water level elevation in a wetland must be higher than the elevation of the outlet, where a significant topographic gradient has to be present to induce surface outflow.
2. Topographic connectedness (shallow depression) with adjacent wetlands determined the inflow and outflow patterns. Isolated wetlands had less outflow.
3. The combination of rainfall input and ET output determined the water storage and was

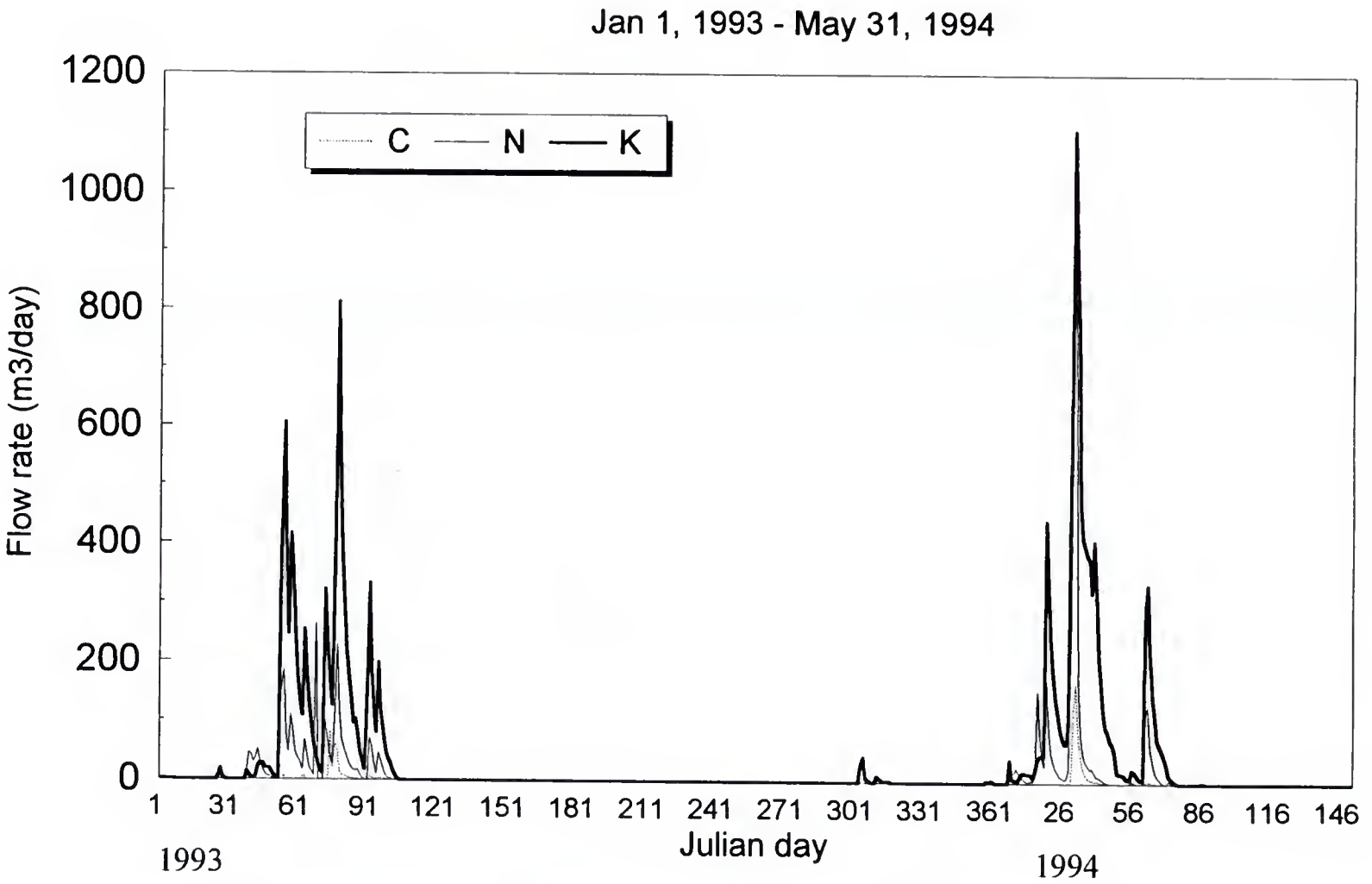


Figure 4.41. Hydrographs of surface outflows from wetlands from 01-01-1993 to 05-30-1994.

the major controlling factor for wetland runoff. Moderate rainfall in winter when ET was the lowest could generate significant runoff, but high rainfall in summer time, when ET-induced storage was the highest, might not generate surface runoff.

Variable Source Areas in Flatwoods

By definition, variable source areas are those areas that directly contribute to storm flow. If the assumption is valid that no surface flow exists in most of the forest uplands, the variable source areas in flatwoods should be confined to wetlands, their vicinities and interfaces.

Surface flow occurred only after the water table exceeded the palmetto line, and the water table - saturated surface area (WT-A) relationships approached linearity (Figures 3.13, 3.14, 3.15). Measured outflows and corresponding estimated flooded surface areas during the study period (Figure 4.42) shows that the surface outflow increased exponentially with the expansion of the wetland surface area. When the area of the surface water passed a certain critical value, the outflow rate increased dramatically. Table 4.10 presents the maximum source area values during the investigation period, which have been estimated from the WT-A relationships. The wetland surface area could expand as much as 2.1 times (K wetland) of the area delineated by the palmetto line during high water table conditions. The C wetland, without surface inflow from adjacent wetlands, had the lowest maximum expansion (1.3 times). The expansion of the variable source areas during selected storms has been summarized in Table 4.11. During wet seasons when surface runoff occurred, additional water inputs from rainfall or inflow substantially enlarged the variable source

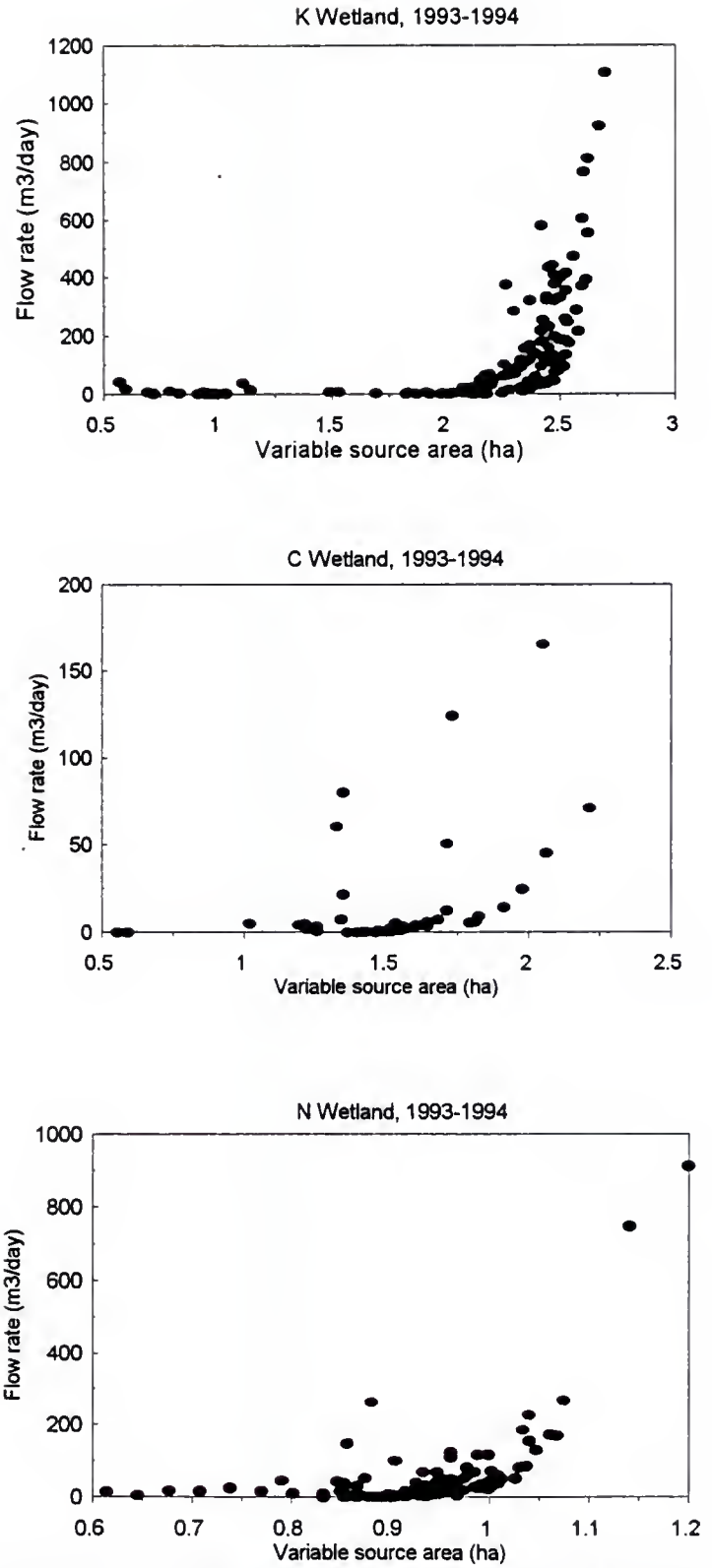


Figure 4.42. Surface runoff from wetlands increases with the expansion of the variable source areas.

Table 4.10. Maximum source area of wetlands during January 1993 - April 1994.

Pond	Elevation of Palmetto line (m)	Pond surface area delineated by palmetto line (ha)	Maximum water table elevation (m)	Maximum pond surface area (ha)	Date of occurrence
C	30.000	1.10	30.130	2.231	02-01-94
K	29.890	1.25	30.069	2.668	01-31-94
N	28.449	0.92	28.555	1.20	01-31-94

Table 4.11. Variable source area dynamics during storm events in 1993-1994.

Pond	Date of storm events	Rainfall amount (cm)	Rainfall duration (hour)	Water table rise (cm)	VSA expansion (%)
C	03-13-93	3.3	6	4.0	25.6
	03-17-93	3.6	12	4.3	27.8
	03-31-93	3.2	5	3.7	23.4
	01-29-94	4.5	26	4.9	32.3
	03-02-94	4.5	13	1.5	9.1
K	02-22-93	6.0	10	6.1	23.2
	03-13-93	3.3	6	3.4	9.8
	03-17-93	3.6	12	4.0	8.0
	03-31-93	3.2	5	4.0	7.3
	01-29-94	4.5	26	4.3	10.8
	03-02-94	4.5	13	6.7	20.4
N	02-22-93	6.0	10	6.1	24.5
	03-13-93	3.3	6	3.4	13.4
	03-17-93	3.6	12	4.0	14.6
	03-31-93	3.2	5	4.0	15.5
	01-29-94	4.5	26	4.3	14.1
	03-02-94	4.5	13	6.7	27.1

areas. Flooded wetland surface area might increase as much as 32.3% in a storm event with a 3-7% increase per cm of rainfall input. It was noted that the water level rise was higher than the rainfall depth of a storm. This disproportionality suggests the capillary fringe effects in the tension-saturated zone developing near pond margin areas might have profound influence on the expansion of variable source areas of wetlands. However, whether the surface and groundwater inflows have also played a part in this process is not clear, and more detailed quantitative studies are needed. Compared to the traditional variable source area concept developed for hilly regions, new features of the variable source area (VSA) forflatwoods are:

1. The VSA develops in wetlands when the water table is high enough to induce surface flow; it is present only during wet seasons.

2. Surface runoff generated from wetlands or other depression areas increased exponentially with the expansion of variable source areas.

3. Expansion of the VSA after a critical elevation is extremely rapid during storm events, while its contraction is slow due to slow net outflow and ET.

4. The wetland and upland systems in flatwoods are highly interconnected through the surficial groundwater aquifer at the land-water interfaces; surface water in the variable source area represents the exposure of the groundwater reservoir to the atmosphere.

5. Groundwater table rise and presence of a capillary fringe play a significant role in developing and sustaining the saturation areas; surface inflows also contribute to the development of the VSA.

One of the important wetland values is flood control by storing onsite storm water

in depressions and reducing storm water runoff downstream during storm events (Mitsch and Gosselink). Riekerk (1992) suggested that the average annual runoff decreased somewhat with an increase of percent cypress wetlands area based on statistical data of 10 flatwoods watersheds. The reasons of this decrease of runoff were hypothesized as: 1) Wetlands had more deep groundwater loss than pine uplands; 2) Cypress wetlands had more ET than pine uplands; and 3) The 'wetland-irrigated' interface areas had higher ET. However, this analysis was for the annual scenarios, and for different seasons, and care must be taken to evaluate flood control effects of cypress wetlands. In flatwoods, significant stormflow or 'flooding' occurred only in wet winter seasons when the wetlands were filled. So during this period, the flood control function of cypress wetlands was limited as compared with pine uplands. In fact, rapidly expanding variable source areas were the origin of storm flow.

Comparison of the available storage of cypress wetlands and pine uplands at different water levels is presented in Figure 4.43. The assumption behind this graph is that both the wetland and the upland have the same water table elevation. It shows that wetlands have the most effect on flood control when the water table is above the 90-cm depth in uplands. The available water storage increases almost linearly in the 0-30 cm depth zone. When the water table depth is below 90 cm, there is little difference in the available storage for infiltration between the upland and the wetland. Upland soils have lower soil moisture content than wetlands soils.

In summary, cypress wetlands can store more storm water in the depressions as well as in the soil pores below the pond bottoms than uplands. However, in extreme high water table conditions, when stormflow is generated by rain-on-water mechanisms, the flood

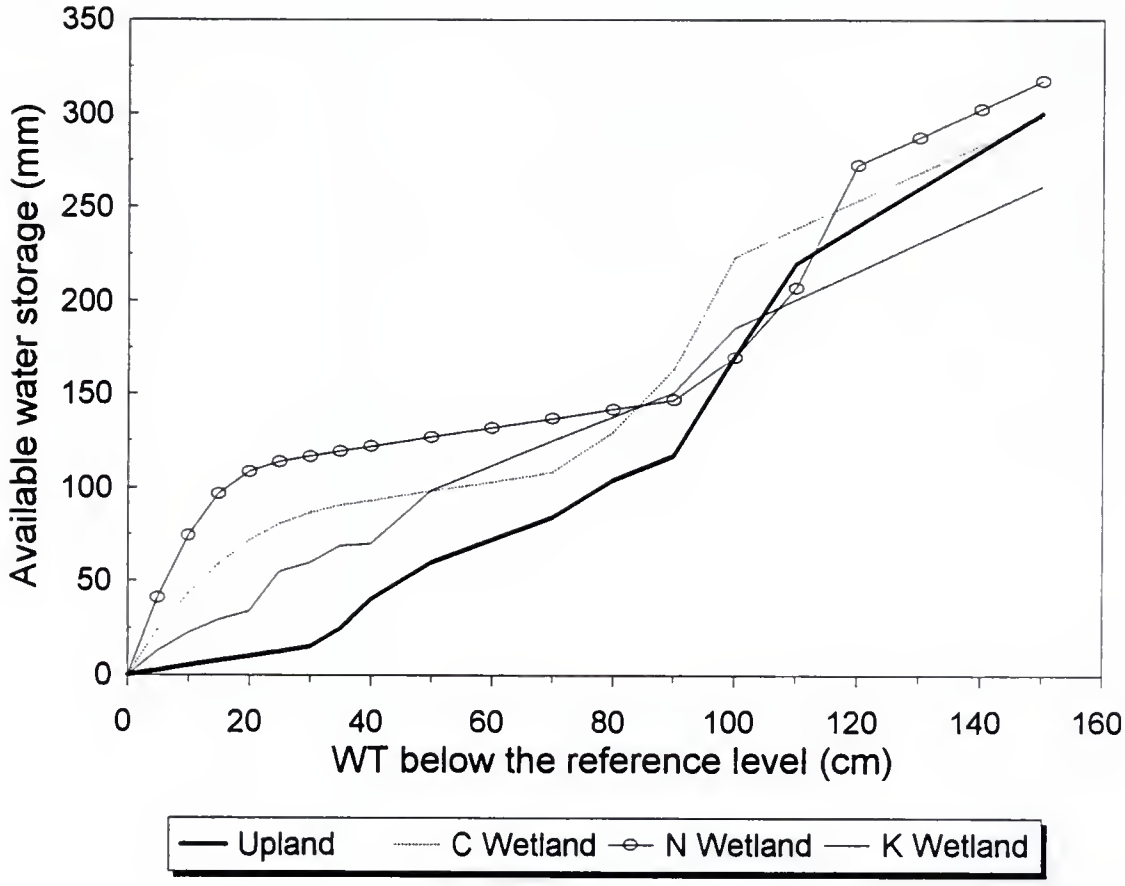


Figure 4.43. Comparison of the available water storage in an upland and three wetland systems under different water table conditions.

control values of cypress wetlands are diminished and wetlands become the source of stormflow runoff.

Water Balances

Water balance or water budget analysis is an effective approach to study water cycles and identify the relative importance of individual components in hydrologic ecosystems. In practical applications, it is also a convenient way to estimate the components which are very difficult to quantify experimentally (e.g. ET). In this section, the monthly water balances of the three cypress wetlands and two pine uplands will be presented. The monthly ET estimated by the water balance equation was compared with the pan evaporation model. Problems in establishing water balances in pine flatwoods will be discussed.

Cypress Wetlands Water Balances

Boundary parameters used in establishing the wetlands water balance have been listed in Table 4.12. Detailed monthly hydrology information of the three wetlands from May 1993 to April 1994 is presented in Table 4.13. The monthly ET loss was estimated in this table by calculating the water storage change, groundwater inflow/outflow, surface inflow/outflow and net precipitation.

As mentioned in Chapter 3, no recording flumes were installed at the inlets of the K and N wetlands, and the surface inflow was calibrated by periodic measurements of flow velocity and the stage height at the culverts. During the process of estimating ET using existing data, large errors (Table 4.13, negative values of ET) were found for the inflow

Table 4.12. Wetland boundary parameters used in water balance calculation.

Wetlands	C	K	N
Elevation of the bottom boundary (m)	28.814	28.065	27.400
Elevation of the top boundary (m)	30.379	30.330	28.600
Total surface area (m^2)	13500	13000	6400
Maximum volume of surface water (m^3)	5082	5368	1283
Maximum volume in the soil zone (m^3)	16046	17057	6454
Soil porosity	0.4	0.4	0.4

components of the K and N ponds possibly due to large measurement errors. Because no surface inflow occurred at the C wetland system, the estimated values of ET for this system as calculated by the water balance is believed to be reasonably accurate. The ET values of K and N wetlands in the months with obvious inflow measurement errors were assumed to have the same value as the C wetland as an alternate way to estimate ET. Surface inflows to the K and N ponds were then estimated based on the ET-corrected water balance for these months.

Monthly water balances of the three wetlands including rainfall, interception, ET, surface inflow and outflow, and the change in water storage are presented in Figure 4.44

Table 4.13. Calculation of monthly wetlands water balances with uncorrected field data.

C Month	Rain (mm)	Ele (m)	Vp (m3)	Vu (m3)	Ap m2	SMC m3/m3	STO (m3)	Si (m3)	So (m3)	GWi (mm)	GWo (mm)	Inter (mm)	ET (mm)
5	58	29.861	343	2255	3535	0.32	517	0	0	6	2	14	55
6	135	29.837	264	2499	3076	0.32	510	0	0	10	2	21	127
7& 8	157	29.819	212	2690	2684	0.32	505	0	0	20	12	31	196
9	113	29.325	0	9148	0	0.31	441	0	0	10	0	28	83
10	215	29.386	0	8324	0	0.32	454	0	0	16	6	16	175
11	38	29.733	53	3692	1146	0.32	487	0	0	10	6	6	30
12	62	29.767	100	3281	1666	0.32	493	0	0	12	6	5	57
1	218	29.797	158	2934	2213	0.32	500	0	297	20	8	14	40
2	26	30.135	2133	345	9534	0.32	661	0	190	4	14	6.6	56
3	80	30.017	1158	963	7130	0.32	585	0	11	0	16	12	79
4	37	29.962	802	1351	5722	0.32	557	0	0	0	12	4.81	91
5	41	29.721	40	3842	969	0.32	486						
K Month	Rain (mm)	Ele (m)	Vp (m3)	Vu (m3)	Ap m2	SMC m3/m3	STO (m3)	Si (m3)	So (m3)	GWi (mm)	GWo (mm)	Inter (mm)	ET (mm)
5	58	29.843	484	1447	3887	0.32	553	0	0	0	2	11	97
6	173	29.428	0	6358	0	0.35	499	0	0	2	1	56	127
7/7	40	29.492	0	5526	0	0.32	491	0	0	2	2	10	150
8	98	28.63	0	16732	0	0.28	396	0	0	0	0	22	32
9	113	28.999	0	11935	0	0.28	408	0	0	2	2	26	122
10	227	28.706	0	15744	0	0.28	309	0	71	6	3	37	25
11	38	29.819	395	1670	3520	0.32	545	0	41	5	4	4	38
12	62	29.803	341	1824	3249	0.32	540	0	12	2	6	6	49
1	223	29.797	322	1883	3141	0.32	538	959	4784	5	5	21	-237
2	26	30.062	2067	183	10964	0.32	683	6158	4882	0	6	6	164
3	80	29.989	1331	396	8872	0.32	625	1200	1385	0	13	10	70
4	37	29.919	832	807	5498	0.32	584	0	0	0	11	5	88
5	41	29.654	35	3455	888	0.32	506						
N Month	Rain (mm)	Ele (m)	Vp (m3)	Vu (m3)	Ap m2	SMC m3/m3	STO (m3)	Si (m3)	So (m3)	GWi (mm)	GWo (mm)	Inter (mm)	ET (mm)
5	58	28.274	8	868	289	0.32	394	0	0	8	2	16	108
6	143	27.907	0	3209	0	0.26	333	0	0	8	0	29	87
7	53	27.967	0	2825	0	0.32	368	0	0	8	2	24	172
8	121	27.402	0	6441	0	0.23	231	0	0	8	2	27	55
9	115	27.542	0	5545	0	0.25	276	0	0	8	2	31	133
10	223	27.408	0	6403	0	0.23	233	0	0	8	4	32	-1
11	38	28.392	192	297	3208	0.32	430	0	0	8	8	6	41
12	62	28.375	142	356	2667	0.32	421	0	0	4	6	6	55
1	224	28.374	139	359	2639	0.32	421	154	2798	16	6	16	-307
2	26	28.526	835	82	5837	0.32	533	596	479	12	6	6	109
3	80	28.45	427	160	4680	0.32	468	577	381	4	10	15	128
4	37	28.392	191	297	3208	0.32	430	0	0	4	10	5	78
5	41	28.09	0	2038	0	0.32	378						

Notes:
Rain=monthly total rainfall
Ele = water table elevation on the first day of the month
Vp = surface water volume on the first day of the month
Vu = volume of the unsaturated zone on the first day of the month
Ap = area of surface water on the first day of the month
SMC = soil moisture content in the unsaturated zone on the first day of the month
STO = total water volume in the wetland on the first day of the month
Si = total monthly surface inflow volume
So = total monthly surface outflow volume
GWi = total monthly groundwater inflow volume
GWo = total monthly groundwater outflow volume
Inter = total monthly canopy interception
ET= total monthly evapotranspiration (excluding canopy interception)

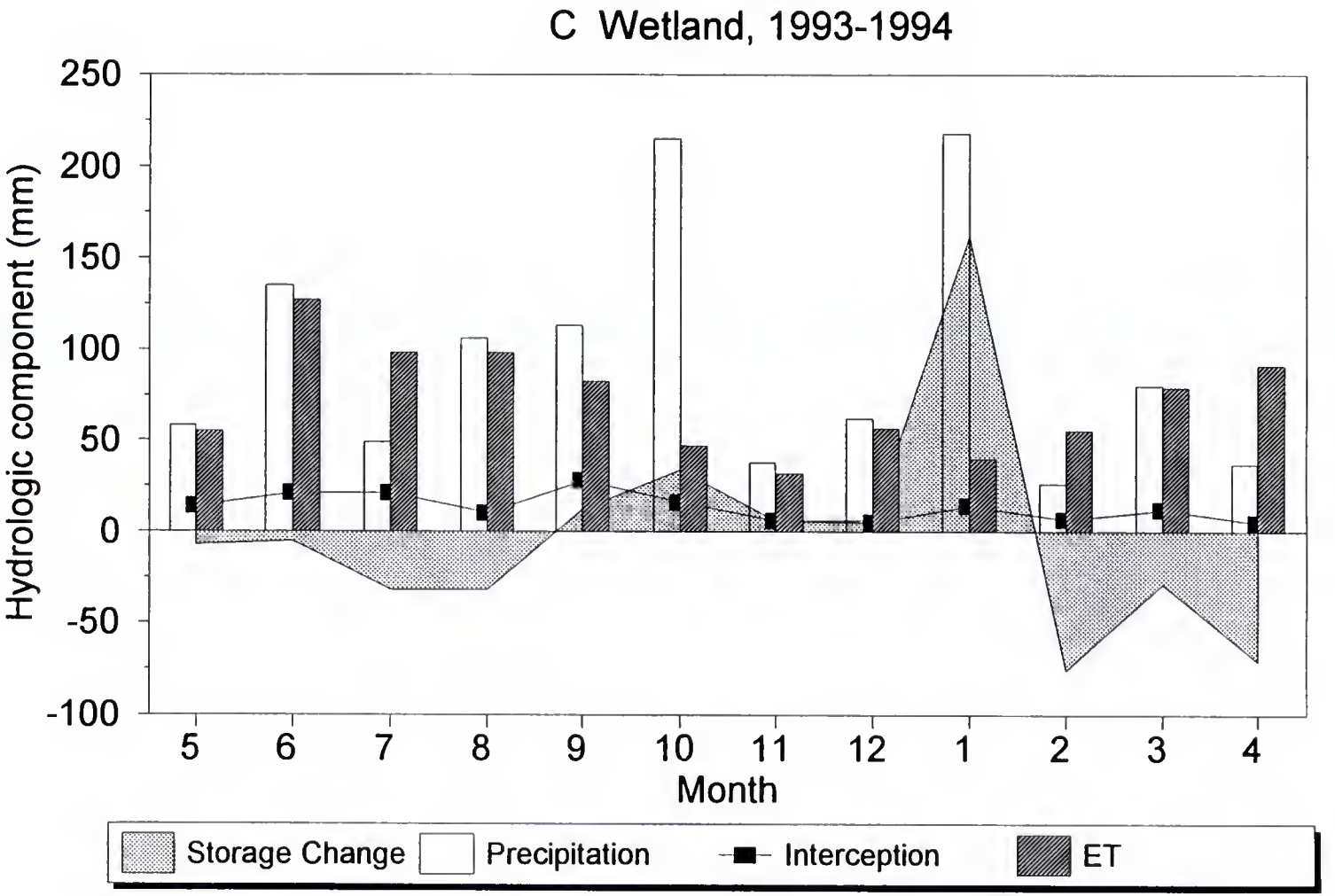


Figure 4.44. Monthly water balances of the C wetland from May 1993 to April 1994.

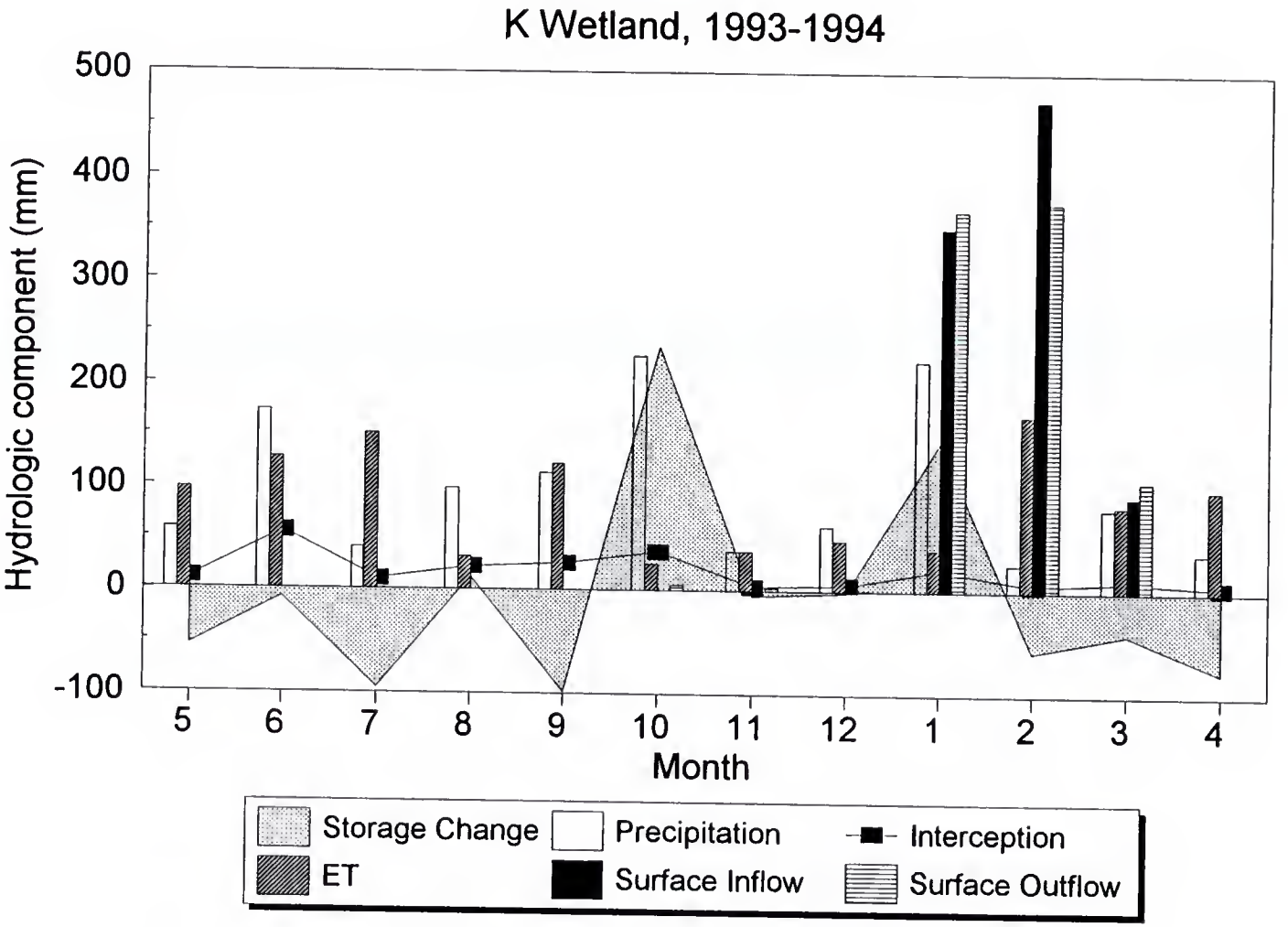


Figure 4.45. Monthly water balances of the K wetland from May 1993 to April 1994.

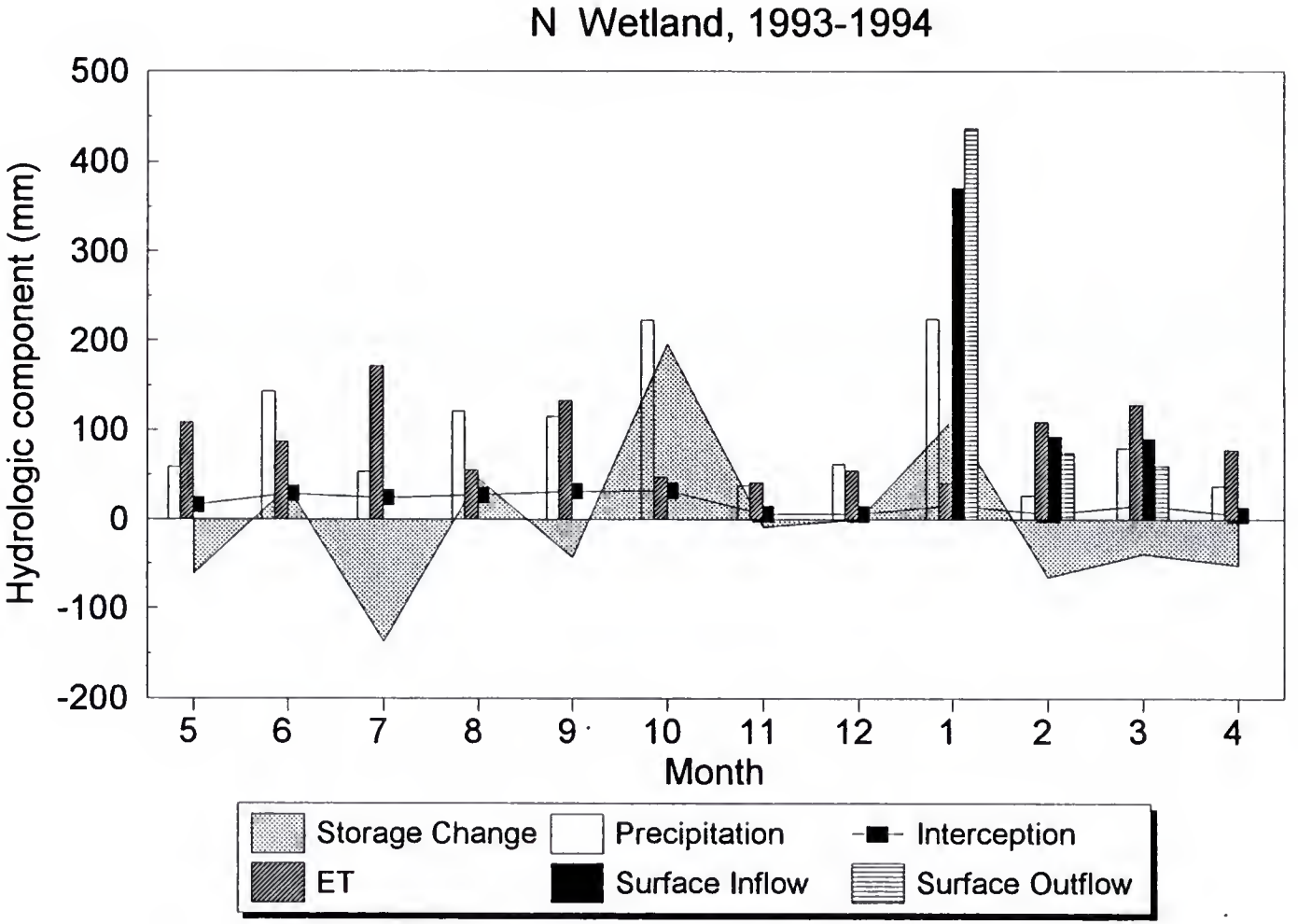


Figure 4.46. Monthly water balances of the N wetland from May 1993 to April 1994.

through Figure 4.46. In those figures, ET represents water loss through plant transpiration and evaporation at the soil/water surface. The lateral groundwater flow and the groundwater deep seepage components have not been included in those0 figures due to their insignificant quantities. The data show that total evapotranspiration (ET + canopy interception) was higher than rainfall in the spring and summer months from March to August and that the water storage tended to decrease. In contrast, the rainfall amount was higher than evapotranspiration loss in the fall and winter seasons, and the water storage tended to increase. As long as the wetlands were full, additional inputs to the systems flowed out directly. In addition to rainfall, effects of surface inflow and outflow dominated the hydrologic components in wetlands during the winter seasons. Water loss by canopy interception was also a significant component from May to October when cypress needles were on the trees.

Annual total hydrologic inputs and outputs from each system have been summarized in Table 4.14 and graphically depicted in Figures 4.47 through 4.50. The data show that the major water input to the C wetland, a relatively isolated wetland without surface inflows, was precipitation and the dominant output was evapotranspiration (including canopy interception). On average, over 83% and 14% of incoming rainfall returned to the atmosphere by plant transpiration and soil/water evaporation, plus canopy interception, respectively. However, because K and N wetlands were connected with adjacent wetlands, significant surface inflow and outflow were observed during the wet seasons in the winter months. Water cycles in those two wetlands were different from the C wetland. The residence times of water and nutrients of K and N wetlands were expected to be shorter than

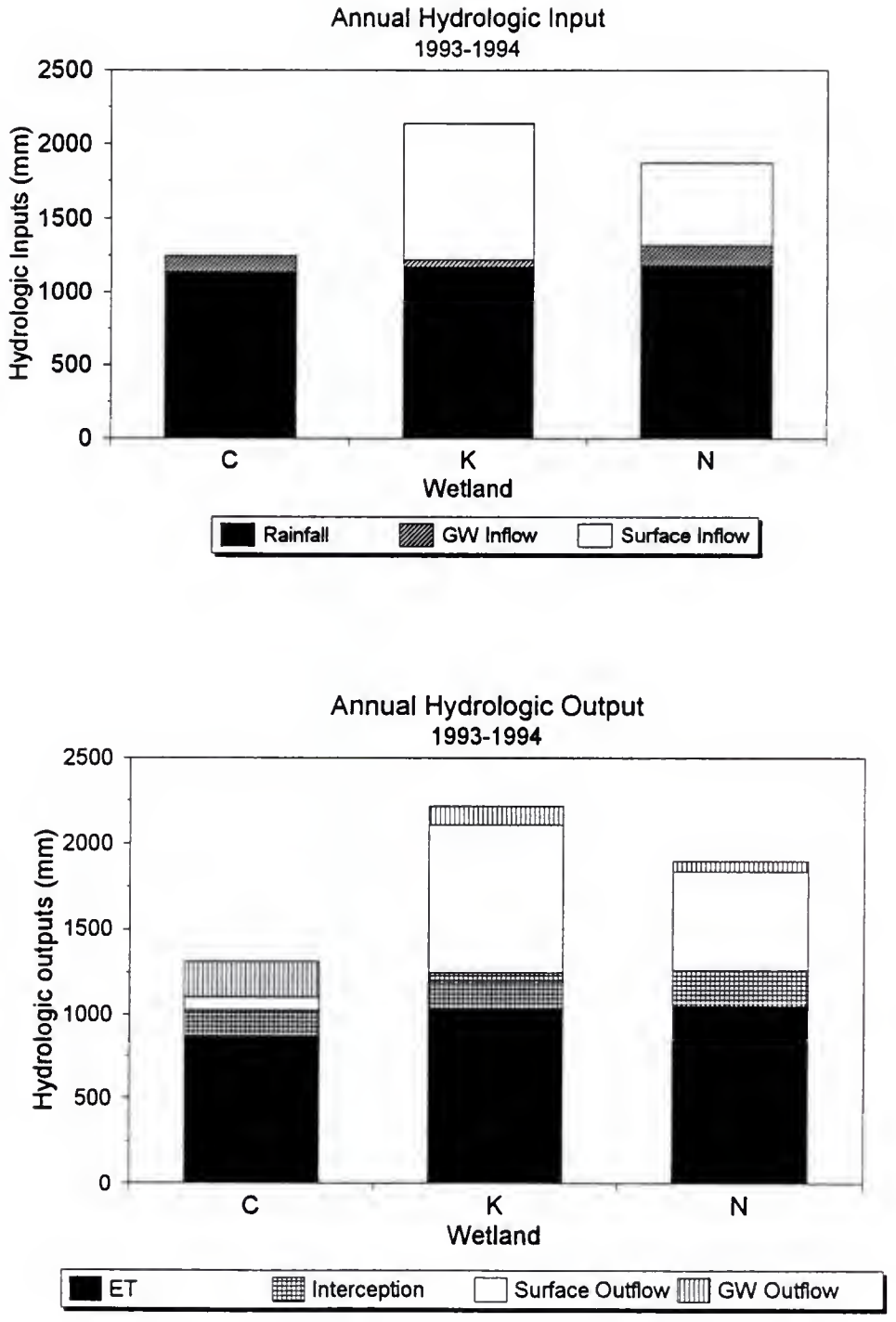
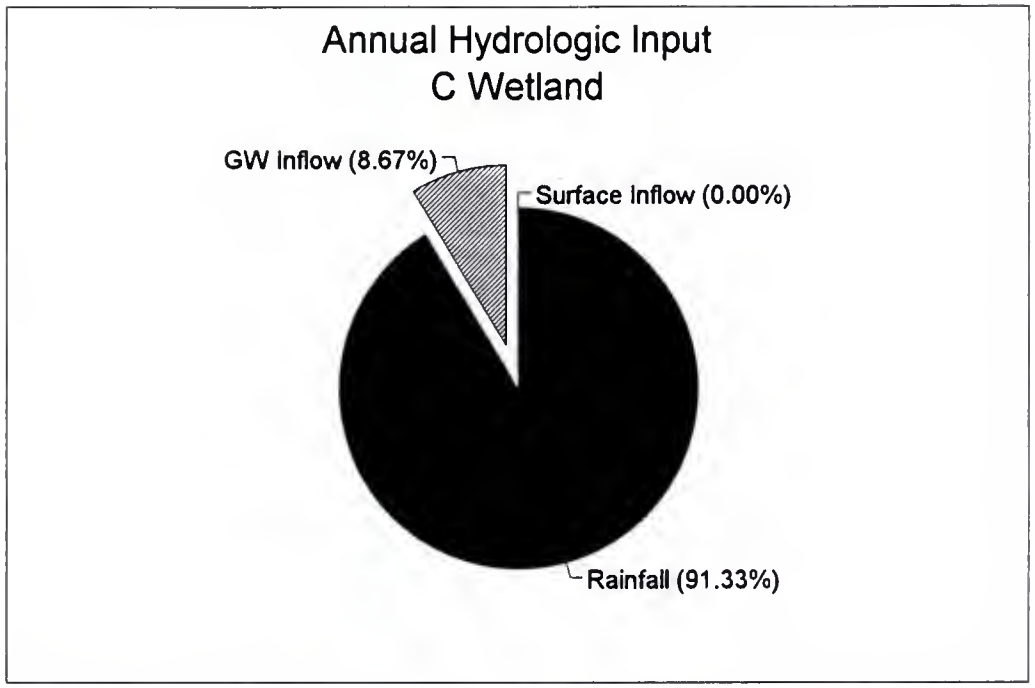


Figure 4.47. Annual hydrologic inputs and outputs of the three wetlands during May 1993 - April 1994.



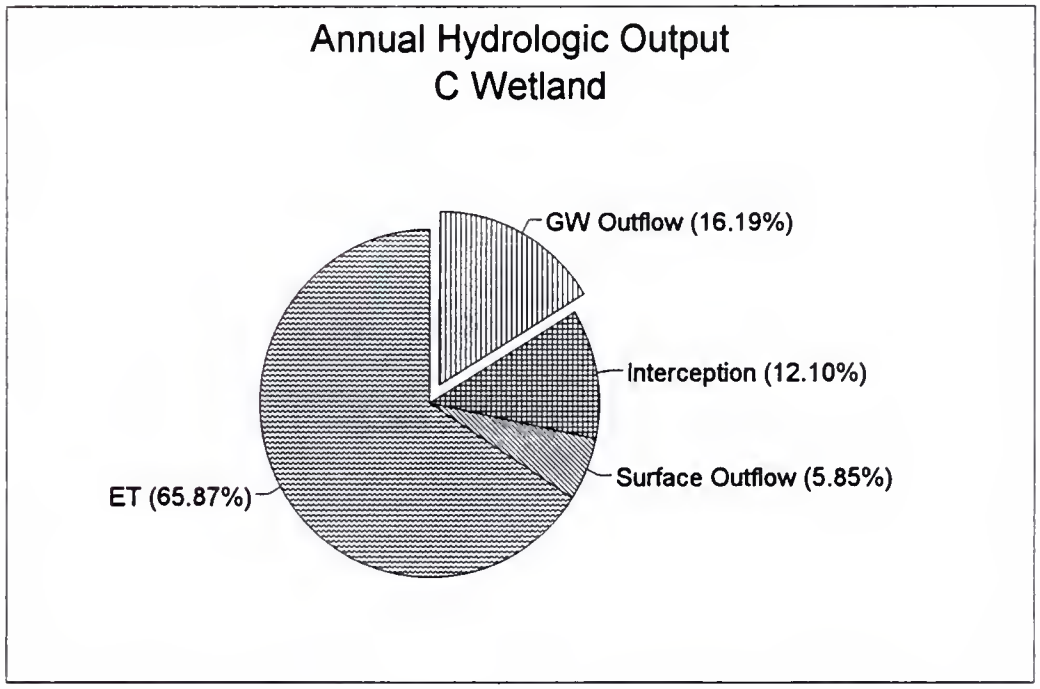
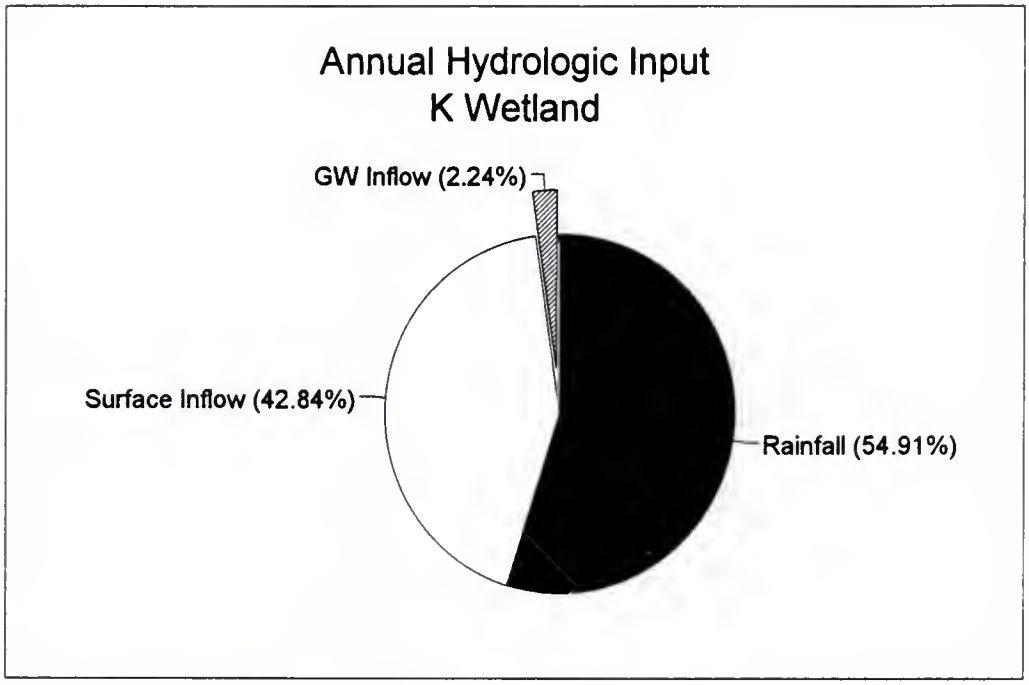


Figure 4.48. Annual hydrologic inputs and outputs of the C wetland during May 1993 - April 1994.



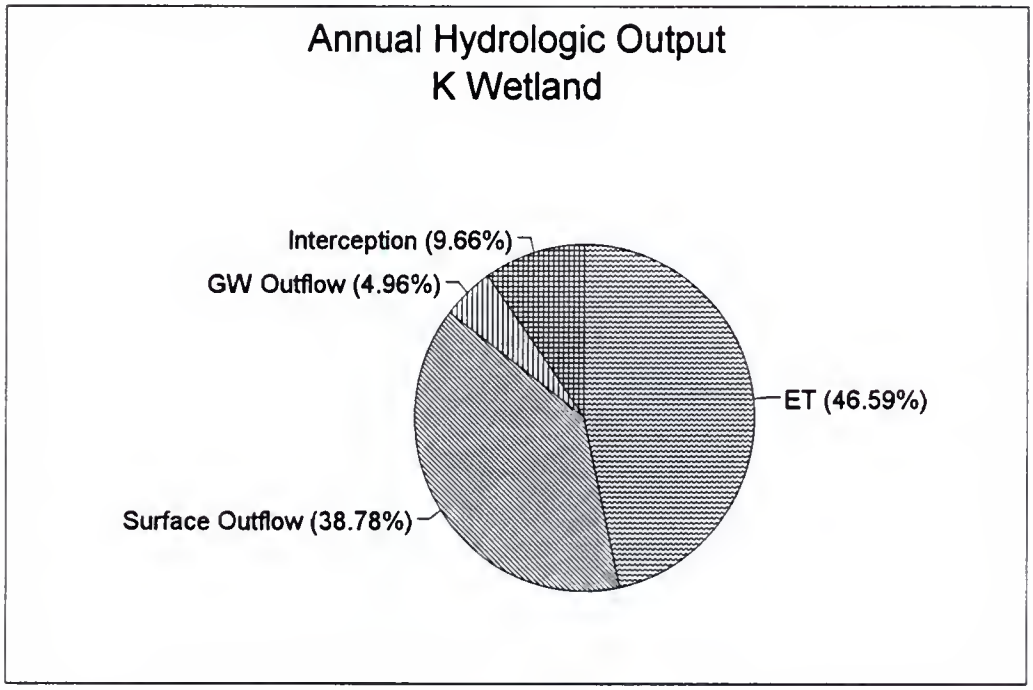
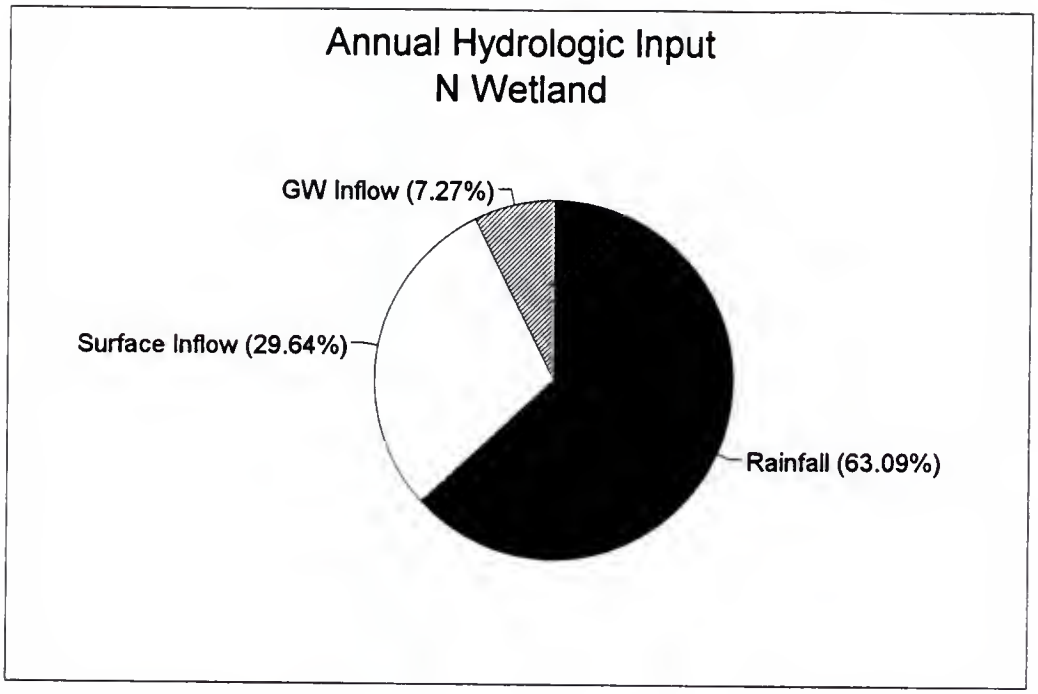


Figure 4.49. Annual hydrologic inputs and outputs of the K wetland during May 1993 - April 1994.



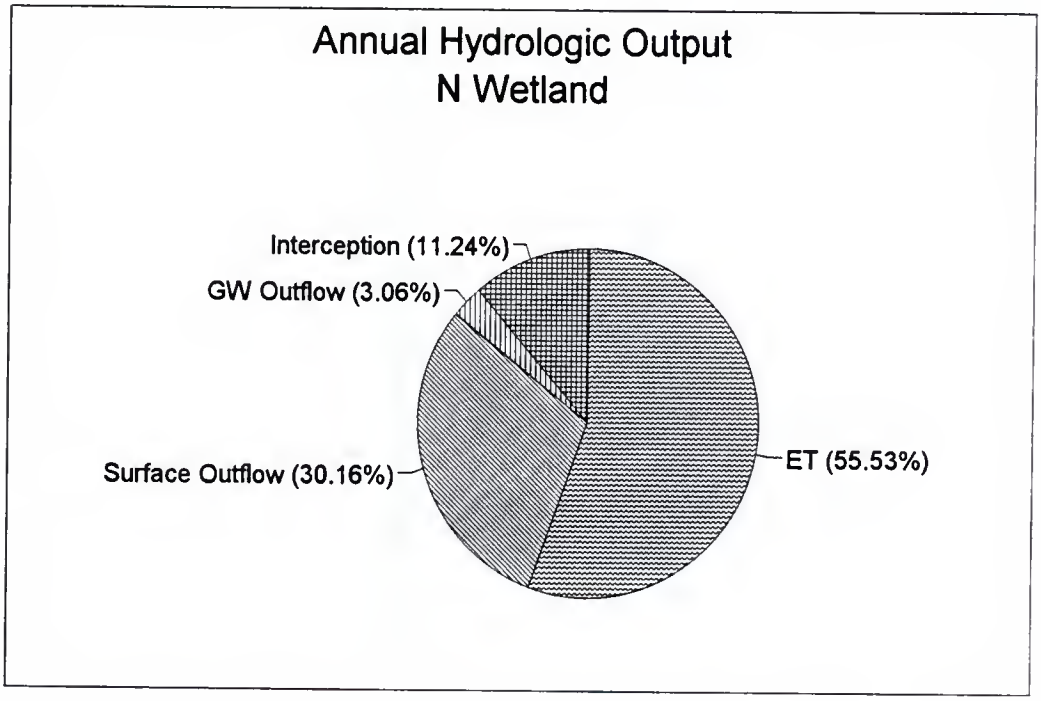


Figure 4.50. Annual hydrologic inputs and outputs of the N wetland during May 1993 - April 1994.

Table 4.14. Annual wetlands water balances during May 1993 - April 1994 (mm).

	Wetland	C	K	N
	Precipitation	1137	1175	1180
	Groundwater inflow	108	48	136
	Surface inflow	0	917	554
Inputs	Subtotal	1245	2140	1870
	Canopy interception	158	214	213
	Groundwater outflow	212	110	58
	Surface outflow	77	860	572
	Evapotranspiration (excluding canopy interception)	863	1033	1052
Outputs	Subtotal	1310	2217	1895
Change in storage[†]		- 65	- 77	- 25

[†]A negative value indicates decrease in storage.

that of the C wetland. Both inflow and outflow amounts for the K and N wetlands were high and of similar magnitude. Cypress wetlands characteristic of flow-through hydrology, such as the C and N wetlands, were neither water sinks nor water sources. Apparently, for all of the three wetlands, the groundwater flow amount was relatively low and was not a significant factor to influence the wetland function.

Pine Uplands Water Balances

Topographical differences between a wetland and its associated upland system in

flatwoods significantly alters the hydrology and vegetation distribution in those two landscape types although the gradation is well recognized. Since overland flows rarely occurred in the pine uplands, and the lateral and vertical groundwater movement was limited in certain areas, the water balance equation may be simplified to:

$$\text{Precipitation - Interception - ET = Change in Storage}$$

or

$$P - P_i - ET = \Delta S$$

where, ET = transpiration of plants + evaporation from the soil surface.

Such monthly water balances for May 1993 - April 1994 have been presented for the C and K uplands in Table 4.15. It shows that the C upland had higher annual water loss (1158 mm, ET + P_i) than its wetland counterpart (1021 mm, Table 4.14). Water loss by ET+P_i from the K upland (1159 mm) was less than that from the K wetland (1247 mm, Table 4.14). Erratic patterns of estimated monthly ET for K upland were found, probably due to the occurrence of surface flow during the high water table periods on this site. In addition, the water table recorder for K upland was located on a flatter site and lateral drainage might have been significant during the winter seasons. Thus, higher uncertainty and measurement errors may have existed in the calculation for the K upland.

Pan ET models for Cypress Wetlands and Pine Uplands

The above water balance analysis showed that evapotranspiration (including canopy interception) is the major water loss from forested flatwoods systems. Although the surface outflow could be significant for any one single wetland, surface runoff from the flatwoods

Table 4.15. Monthly water balances for pine uplands during 1993-1994† (mm).

Uplands	C				K			
Month	P	P_i	ET	ΔS	P	P_i	ET	ΔS
May(1993)	58	13	93	-48	58	10	74	-29
Jun	143	22	93	28	143	27	96	20
Jul	53	14	110	-71	53	19	180	-145
Aug	104	9	115	-20	98	23	64	11
Sep	113	25	95	-7	113	20	94	-1
Oct	215	22	67	126	227	39	23	165
Nov	38	4	37	-3	38	3	69	-34
Dec	62	4	38	19	62	7	15	40
Jan (1994)	217	11	51	155	223	25	71	127
Feb	26	5	82	-61	26	6	97	-78
Mar	80	12	117	-49	80	13	86	-19
Apr	37	7	111	-81	37	6	93	-62
Annual total	1146	148	1010	-12	1158	198	961	-2

P = monthly precipitation above the forest canopy;
P_i = interception by vegetation of overstory and understory layers;
ET = evapotranspiration excluding canopy interception; and
ΔS = change in water storage in a month; negative values indicate decrease in storage.

landscape as a whole is expected to be low due to the complex processes of surface water - groundwater interactions. The Class A evaporation pan provides a convenient way to quantify potential evapotranspiration (PET) for specific atmospheric conditions. Actual evapotranspiration from wetlands or other land types can be approximated by multiplying PET by a crop coefficient (Veihmeyer, 1964; Kadlec, 1989).

Figure 4.51 presents a comparison between the total monthly evapotranspiration (ET) (including canopy interception) from C wetland and upland estimated by the water balance method and by the Pan ET model. A coefficient of 0.7 was used by the pan ET model to fit the real data points. The pan ET model had a good fit to 'measured' data points throughout the year, but over estimated upland ET only during the summer months (Figure 4.52). In contrast, ET of K and N wetlands estimated by the water balance method shows unpredictable patterns, presumably due to inaccuracies involved in the surface flow measurements (Figure 4.53).

This analysis suggests that water loss by ET from cypress wetlands is somewhat less than that from pine uplands and is about 70% of pan ET. Significant variability and uncertainty are involved in the estimation of ET by the water balance method for wetland-upland systems. Previous studies suggested cypress wetlands conserved water by consuming less water per gram dry matter accumulation than terrestrial ecosystems (Ewel and Odum, 1984). Riekerk et al. (1995) recently completed a flatwoods evapotranspiration project on the same C, K, and N systems and found no significant differences of annual ET between the wetland and upland systems.

It seems contradictory that ET of wetlands is less than or equal to that of uplands since the water use by plants in wetlands is unlimited throughout the year. However, as described by Heimburg (1984), the special microclimate of low temperature and wind velocity due to shading effects by the high-density vegetation of cypress domes significantly reduces water vapor movement to the atmosphere. As shown in the previous sections, the water level in the wetlands usually falls below the soil surface, and the wetlands can

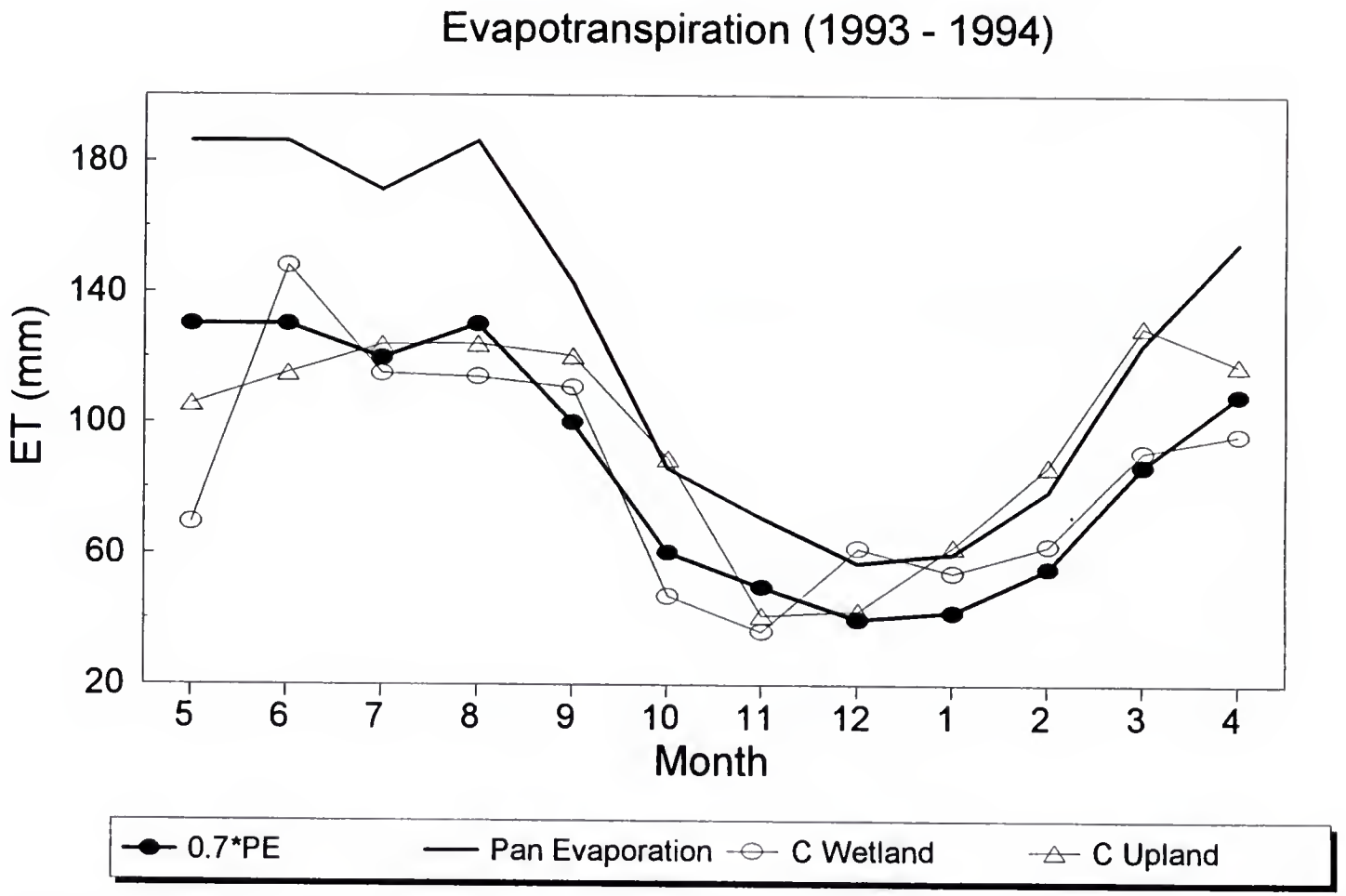


Figure 4.51. Monthly evapotranspiration of the C wetland and upland estimated by the water balance method is fitted by the Pan evaporation model with a coefficient of 0.70.

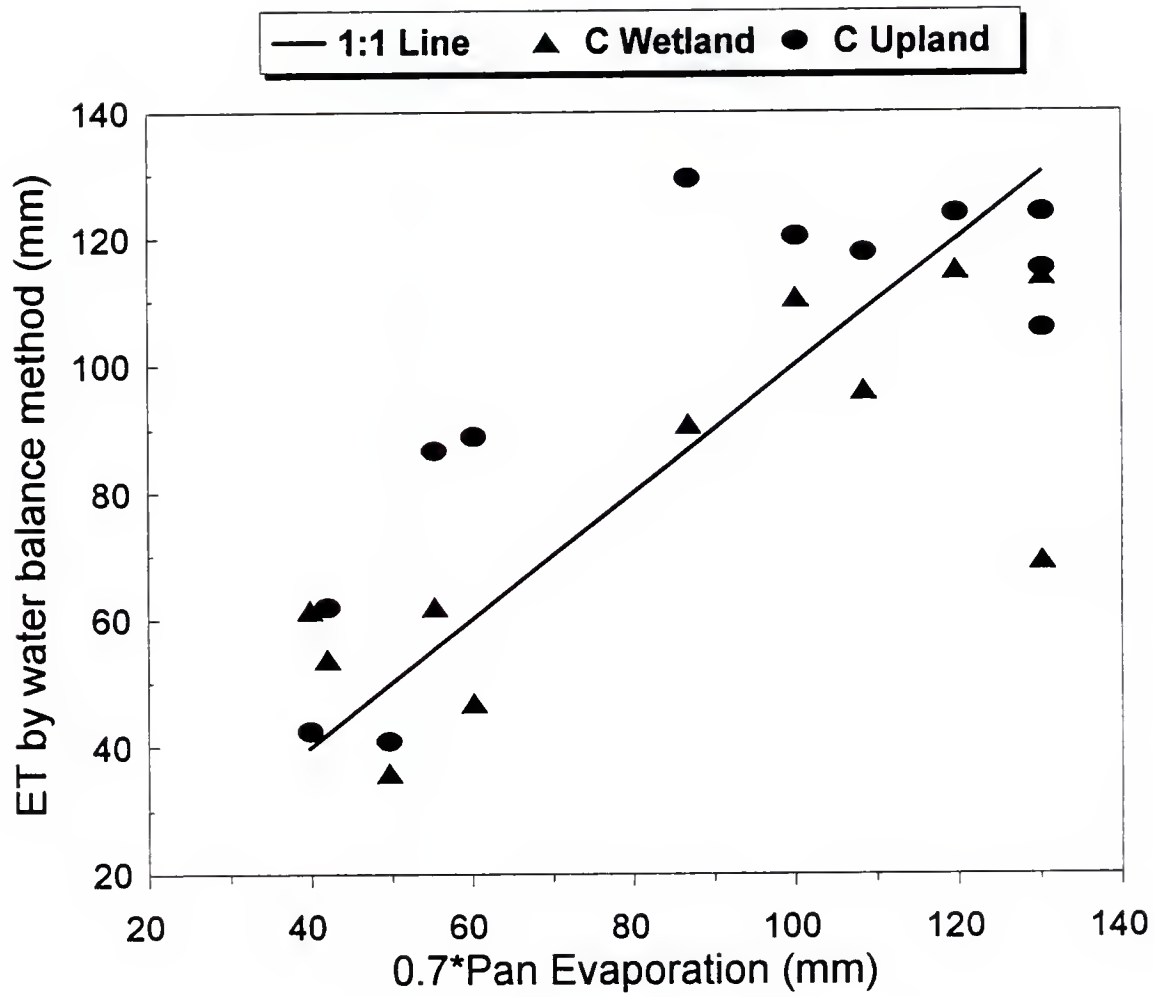


Figure 4.52. Double mass analysis to compare evapotranspiration of the C wetland and C upland estimated by the water balance method and Pan evaporation model with a coefficient of 0.70.

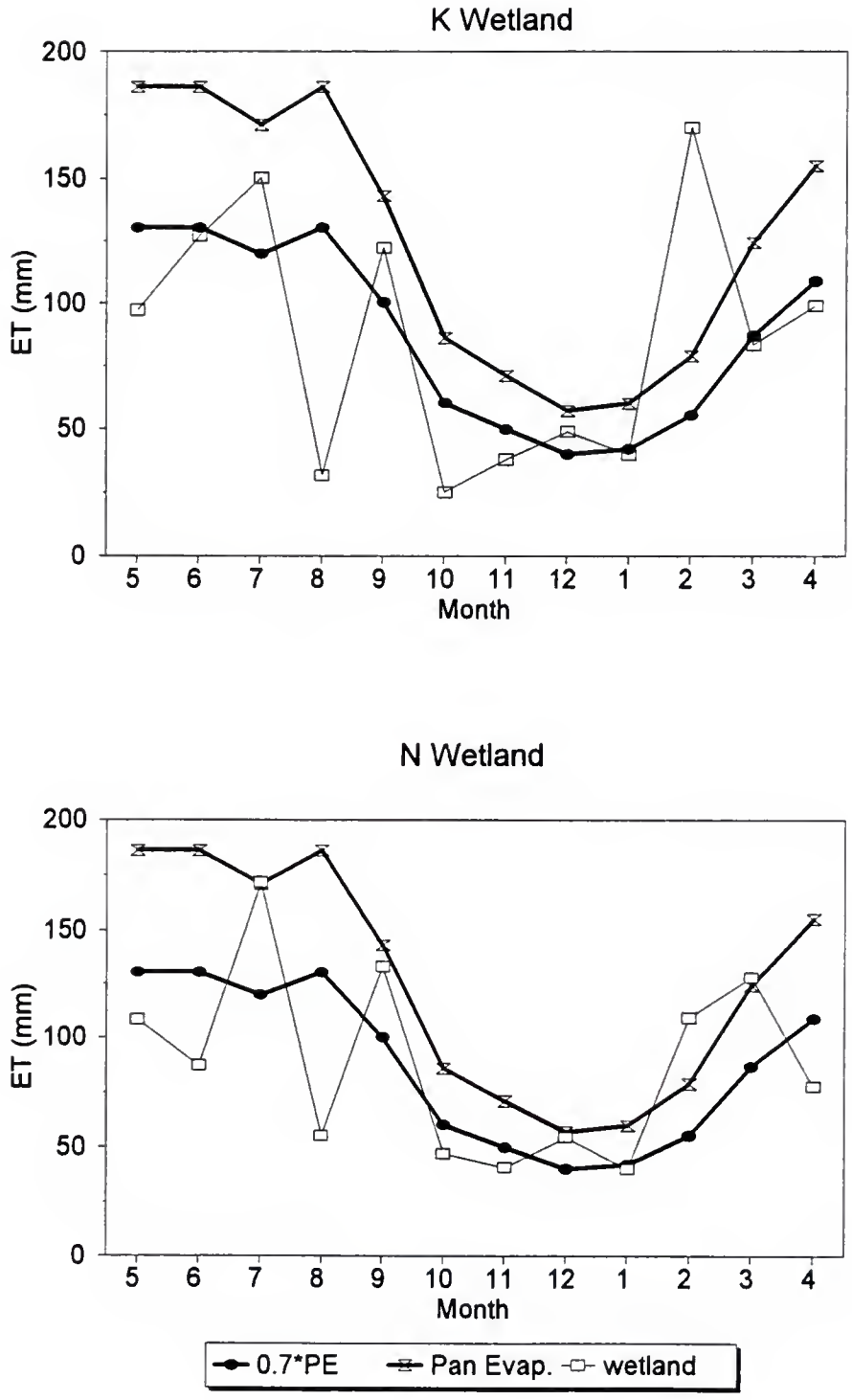


Figure 4.53. Comparison of the evapotranspiration from K and N wetlands estimated by the water balance method and Pan evaporation model with a coefficient of 0.70.

completely dry up in the spring and summer months. During this period, the top 20-cm of undecomposed, porous organic matter may help to reduce evaporation. In the season from November to March, cypress trees lose all the needles, and transpiration and canopy interception loss are at a minimum. Kozlowski (1984) reported that flooding of soils reduced stomatal aperture, transpiration and absorption of water for many plant species including *Quercus macrocarpa*, *Eucalyptus camaldulensis*, *E. globulus*, *Ulmus americana*, *Salix nigra* and *Nicotiana tabacum*. However, it is not clear if pond cypress trees have the same responses during the growing season when the root system is under inundation conditions.

Soil evaporation and shrub transpiration in uplands are expected to be high during high water table conditions since the water supply is abundant and the relative open canopy of slash pine stands and high soil moisture content favors the growth of a dense understory vegetation. However, the low stand density and sparse understory of the pine plantation of the study area facilitates light penetration and air movement, thus generating more ET. In addition, soil surfaces exposed to air by forest floor bedding may also increase soil evaporation loss, especially during the early developmental stages of the upland forest stands.

Water shortage of pine uplands in summer months may occur since the calculated ET loss is far less than the potential ET. In fact, the water storage in the water table aquifer was depleted in the summer months of July and August 1993. Water uses by plants were mainly extracted from the unsaturated zone, which was recharged by rain water from periodic afternoon thunder storms.

Summary and Discussion

Three paired cypress wetland - pine upland ecosystems in flatwoods were instrumented and monitored for three years with the objectives to determine the preferential water pathways and to evaluate environmental effects of different forest management practices. This dissertation reports the hydrological investigation during the pre-treatment period. Research methods in this study were guided by a water balance equation for flatwoods characterized by a high water table level, poorly drained soils, high ET and ill-defined system boundaries. This chapter provided results during the first-phase pretreatment period of the NCASI project. Hydrologic processes in wetland-upland systems including canopy interception, soil moisture dynamics, surface flow, water table dynamics, and groundwater flow were examined with an emphasis upon interactions between aquatic and terrestrial systems. Hydrologic balances including rainfall, canopy interception, ET, surface inflow/outflow, groundwater inflow/outflow, and change in water storage were constructed for both wetlands and uplands.

1. On average, about 16.9 and 15.3% of precipitation was intercepted by cypress wetlands and slash pine uplands vegetation, respectively, and returned to the atmosphere. Canopy interception rates showed high variability depending on the rainfall event characteristics and tree phenology.

2. Spatial distributions of the average soil moisture content in the 0-45 cm layer of wetland-upland systems had the following pattern: wetland 23.9% > wetland margin 16.8% > upland 7.5%. Wetland soils retained a significantly higher soil moisture content during the dry

seasons than the pine upland soils, possibly due to lower ET and high retention capacity of the organic wetland soils.

3. The relationship between the volumetric soil moisture content and groundwater table depth was described by a nonlinear 4-parameter function derived from the Van Genuchten equation. This relationship may be used for a rough but adequate estimation of the initial soil moisture content of different soil layers in the unsaturated soil zone for flatwoods hydrologic modeling.

4. The spatial and temporal variation of the shallow groundwater water table was investigated. As expected, groundwater table depth decreased with lateral distance from forest upland areas toward wetland areas. Although high variability was found on a small scale such as a single wetland-upland system, the groundwater table generally followed the large-scale topographic gradient; that is, the higher the topographic elevation, generally the higher the water table elevation. Similarity between the landscape topography and the groundwater table configuration in these flatwoods may be one of the reasons that most of the cypress ponds were flow-through types.

5. High temporal variation of the water table level was found for both wetlands and uplands. Water table levels in wetlands were found to be higher than the palmetto line (i.e. 38 cm above the bottom elevation at the wetland center) for more than two months, but the water level was below the wetland bottom for about five months of the year 1993. Water table elevations in the upland soils were found to fluctuate more than in the wetlands due to the lower water storage capacity, high ET, *Lisse effect* and *Wieringermeer effect*. The upland water table levels were below the 100-cm and 50-cm depths for 5 and 9 months, respectively,

from May 1993 through April 1994. Wetland margin areas, at least within 25 meters from the palmetto line, could be recharged by the pond surface water when reversal flows of groundwater occurred. A pronounced rise of groundwater table elevation was recorded during rainless nights at the pond margin .

6. A comprehensive index to quantify wetland hydroperiod, which is defined as the duration and frequency of flooding in a cypress wetland, was presented. It included three components, the duration of inundation (DI), the number of times of continuous inundation (CI), and the average water depth of inundation (WT). This index effectively and quantitatively demonstrated the variability of wetland hydroperiods in different years and among wetlands. It can be used to evaluate the change of wetland hydroperiod during the post-treatment period.

7. The groundwater table rise in flatwoods soils during storm events was determined mainly by rainfall characteristics (amount and intensity), as well as initial water table level. The water table in the wetland margin area showed the highest response (14.1 cm rise per cm rainfall) compared with the wetland (9.6 cm/cm) and upland (10.2 cm/cm) sites. In contrast to this specific yield, the variable storativity concept was used to explain the spatial variability of the water table response.

8. Soil water flux balance equations were developed and used to explain water table fluctuations in the variably-saturated flatwoods soils. Four scenarios were generalized according to responses of uplands water table to rainfall and evapotranspiration.

9. During periods characterized by high water tables, groundwater tended to flow through or into wetlands in most circumstances, but during the spring some wetlands associated with

a flatter topography showed outflow patterns. Reversed water flow from a wetland to the surrounding upland with higher topographical elevation, was believed to be controlled by the differences in the soil porosity, the water loss by ET, and the substrate elevation between the wetland and upland systems of the restricting bottom layer.

10. The saturated hydraulic conductivity of the surficial aquifer, determined by the Bouwer and Rice slug test, varied from 0.5 to 20.0 m/day. Due to the low gradients in groundwater table elevation, the flow velocity for solutes in flatwoods was less than 10.0 cm/day.

11. Surface water of wetlands in flatwoods represents the degree of exposure of the surficial water table aquifer. Most surface flow occurred from January to March during the winter season when the water table levels were high and the maximum wetland water storage capacity had been reached.

12. Exponential relationships were found between wetland discharge rates and the saturated wetland surface areas. The maximum expansion of the wetland surface water area might reach twice that of the area determined by vegetation changes (i.e., the palmetto line); an expansion of 3-7% of the variable source area per cm of rainfall was found during storm flow. It was estimated that surface flow might be generated from 40-60% of the land area of a typical pine flatwoods landscape with 35% of the total area in wetlands.

13. The general Variable Source Area Concept (VSAC) permitted description of the stormflow runoff mechanism in flatwoods watersheds, but special features of the variable source area in flatwoods were identified as follows:

A. The VSAC applies in wetlands when the water table is high enough to induce surface flow; it also applies only during wet seasons.

B. Surface runoff generated from wetlands or other depression areas increased exponentially with the expansion of variable source area.

C. Expansion of the VSA after a critical elevation was extremely rapid during storm events, while contraction is slow due to net outflow and ET.

D. The wetland and upland systems in flatwoods are highly interconnected through the surficial groundwater aquifer at the land-water interfaces; surface water in the variable source area represents the exposure of the groundwater reservoir.

E. Groundwater table rise and capillary fringe play an important role in developing and sustaining the saturation areas; surface inflows also contribute to the development of the VSA.

14. The water balance analysis showed that rainfall and ET provided the major water inputs and outputs for isolated wetlands, but inflow and outflow also provided significant contributions to the water balances for interconnected wetlands. Groundwater flow quantity was relatively small (less than 16% of total input or output) compared with other hydrologic components. Annual precipitation on wetlands and uplands was approximately balanced by annual ET; also annual inflows and outflows had similar values for flow-through type wetlands.

One of the environmental concerns of forest management practices in flatwoods is the chemical contamination generated either by the uses of agrochemicals or the accelerated mineralization of forest residuals. Concerns are for both onsite and offsite locations. This study showed that both lateral and vertical groundwater flows were relatively slow, thus chemical movements from pine uplands to cypress wetlands through subsurface soils should

be minimal. In addition, reversed groundwater flow from wetlands to uplands at some locations and time periods further reduced the chance of contamination of wetlands. The sluggish water movement in soils would allow chemicals to have longer interaction times with soil particles and other biological activities. From the standpoint of water pollution concerns, spring and early summer seasons when upland soils had developed a relatively deep unsaturated zone, are considered to be the best time for forest fertilization and other forest activities. Although interactions between wetland surface water and groundwater in the pond margins were present, the range was generally small and most wetlands were isolated during most of the year. In contrast to the groundwater flow, surface flow in wetlands and inter-wetlands areas was more pronounced and is believed to be the major link between adjacent wetlands and carriers of chemical pollutants in pine flatwoods systems. Disturbance in the wetlands and margin areas may cause more water quality problems than upland areas in flatwoods since these saturated depression areas provide the sources of surface runoff.

Given these hydrologic characteristics of flatwoods, partial harvesting is recommended for forest regeneration because: 1) the effects of forest harvesting in flatwoods are more localized and associated forest management activities may not have a great impact on adjacent areas if the surface flow does not occur; and 2) partial harvesting retains enough ET to keep the water table level low to minimize the extent of saturated areas.

Buffer zones around wetlands in flatwoods may be more effective to protect their aquatic systems than for hilly areas because: 1) buffer zone vegetation may enhance the flow reversal by lowering the groundwater table; and 2) the ET-induced water storage capacity

in the vegetated buffer zone may be sufficient to absorb the local rainfall input and/or surface runoff (solutes) from uplands to prevent them from being transported to wetlands.

Another concern of forest harvesting practices in pine flatwoods is the change of the wetland hydroperiod due to the rise of the groundwater table. This study suggested that the groundwater table elevation was controlled by the combined patterns of rainfall and evapotranspiration. Since the latter is determined by local climate and is relatively stable in an undisturbed system from year to year, the rainfall patterns dictate the wetland hydroperiods. Forest harvesting significantly reduces water loss by plant transpiration and interception, but soil evaporation increases due to the increased available solar energy and ventilation. This study so far can not tell quantitatively the total effects of forest removal on ET and the groundwater table level, but simulation studies in Chapter 5 will provide some information on these topics.

CHAPTER 5
THE FLATWOODS MODEL

Model Development

Model Objectives

The FLATWOODS model is based on the published COASTAL computer program (Sun, 1985). The COASTAL model has not been widely used in the hydrologic simulation community. Nonetheless, its basic model idea and structure are very good and this method offers a high potential for water resource management in the coastal plain regions. An evaluation of the COASTAL model has been made for this investigation with the goal to adapt it to pine flatwoods.

Advantages of the COASTAL model are listed as follows.

1. The COASTAL model is an areal two-dimensional, distributed model using a grid system, where the boundaries of the system can be defined by the user. These features are useful since lateral and vertical boundaries of flatwoods are much more difficult to define compared with other areas with obvious watershed divides and rock beds. Also, a distributed model is superior to a lumped model since a distributed model can account for heterogeneity within a watershed. Consequently, more spatial information can be obtained from model outputs.

2. The COASTAL model couples groundwater flow and surface flow processes. Procedures used in MODFLOW (McDonald and Harbaugh, 1984) and BROOK (Federer and Lash, 1978) models were adapted to handle saturated and unsaturated flow processes in the COASTAL model. Both the MODFLOW model and BROOK models have been popular and effective in dealing with groundwater flow and forest water simulations (Federer and Lash, 1978; Archey and Miller, 1986).

3. The COASTAL model uses a simplified method instead of Richard's equation to solve unsaturated water flow in the unsaturated zones to avoid numerical problems when solving large spatial (>1 km) and temporal (year) scale problems.

4. The COASTAL model was developed for Georgia's coastal geologic conditions that have similar formations as the Florida pine flatwoods.

5. The structured FORTRAN program used by the COASTAL model is easy to understand and flexible enough to allow for modification in practical applications, especially for users already familiar with MODFLOW and BROOK models.

Deficiencies of the COASTAL model include:

1. The COASTAL model was developed, calibrated and verified by runoff data from a large watershed (368 km^2, 1 km grid). It is unknown how well this model will perform for small forested watersheds in the spatial scales of 0.5 - 100 ha.

2. The COASTAL model has not been calibrated and validated with data on evapotranspiration, the spatial distribution of the water table level, and the soil moisture content over time. This deficiency could result in the failure of application by users with interests other than runoff.

3. The interactions between surface water and groundwater in wetland-upland systems are not described explicitly in the model. In the COASTAL model, the grid is so large that the flow between two cells is essentially groundwater rather than surface water-groundwater. This deficiency may result in the failure of investigations of smaller areas where the size of a cell is less than a single wetland with surface water present.

4. The COASTAL model calculates stream flow (Q) from a stream flow rating curve, $Q = f(H)$, where H is the groundwater table stage height. For ungauged small flatwoods watersheds, however, this curve normally is not available. This deficiency may result in the inability to directly apply it to flatwoods which do not have obvious stream channels or stream flow rating curves.

5. The COASTAL model uses a two-dimensional groundwater flow model (Boussinesq Equation) to represent an unconfined groundwater flow system. The third vertical dimension, however, may also be significant in terms of vertical leakage or artesian effects in flatwoods.

6. Effects of water storage within wetlands are not described explicitly. In undisturbed flatwoods, surface runoff from wetlands occurs only when the water level exceeds a critical sill elevation and each wetland has some dead storage as surface water.

This study intends to remedy deficiencies of the COASTAL model as discussed above and to build a new forest hydrological model (FLATWOODS) for cypress wetlands/slash pine upland systems. Major modifications to the COASTAL model include: (1) evapotranspiration components; (2) unsaturated flow procedure; (3) surface flow routing, and (4) variable specific yield and saturated hydraulic conductivity. The structure of the

FORTRAN program code of the new model relies heavily on the COASTAL model. However, subroutines for the unsaturated water flow submodel, evapotranspiration submodels, and input and output formats have been drastically modified.

The resulting FLATWOODS model was developed for pine flatwoods with the following objectives:

1. To predict spatial and temporal hydrologic effects (surficial groundwater table, runoff, soil water flux in the unsaturated zone, evapotranspiration) for forest management purposes.

2. To account for hydrologic heterogeneity and continuity of wetland/upland ecosystems and environmental variables (e.g. precipitation);

3. To develop a tool for forest water management and hydrologic research using easily obtainable watershed and climatic information.

The FLATWOODS model may be classified as a distributed, dynamic (some parameters vary with time), continuous (daily time step) and watershed scale simulation model. It was designed for a flat topographic landscape characterized hydrologically by a storage-based system with a high and dynamic groundwater table. The model can be used to study the surface water-groundwater interactions between wetlands and surrounding uplands. Also, the present model could be used to study water exchanges between the atmosphere, unsaturated soil zone (three layers) and the saturated soil zone (unconfined aquifer). Although the model was built for describing watershed-scale problems, it could be used for virtually any size system (e.g., field scale) if appropriate boundary conditions are provided.

Model Structure

The model imposes a grid over the entire wetland-upland system to distribute the heterogeneous watershed into different, but homogeneous rectangular cells (Figure. 5.1). The physical properties of each cell are assumed to be uniform laterally for each soil layer, but non-uniform vertically in different soil layers. Each cell becomes a modeling unit that holds mathematical equations describing the physical properties. In practice, spatial data for forest lands are rarely available at high resolution with the exception of some readily available parameters such as surface elevation, vegetation and soil types (wetlands vs. uplands), etc.

The model consists of three major submodels, each simulating parts of the hydrologic processes on a daily time step (Figure 5.2).

1. The evapotranspiration submodel.

The evapotranspiration (ET) is a highly significant part of the water balance of flatwoods. Driving forces of the hydrologic system are climatic variables including rainfall and air temperature (evapotranspiration). The daily rainfall and temperature data as model inputs of climatic variables are available from actual field recordings or the local weather station. The ET submodel has three components including a rainfall interception component (I_p) by forest canopies, evaporation from soil/water surfaces, and transpiration through plant stomata. The rainfall interception depends on daily rainfall, leaf area index (LAI) and available canopy interception storage or dryness of the forest canopy. The Penman-Monteith equation has been regarded as the most accurate estimation of potential evapotranspiration

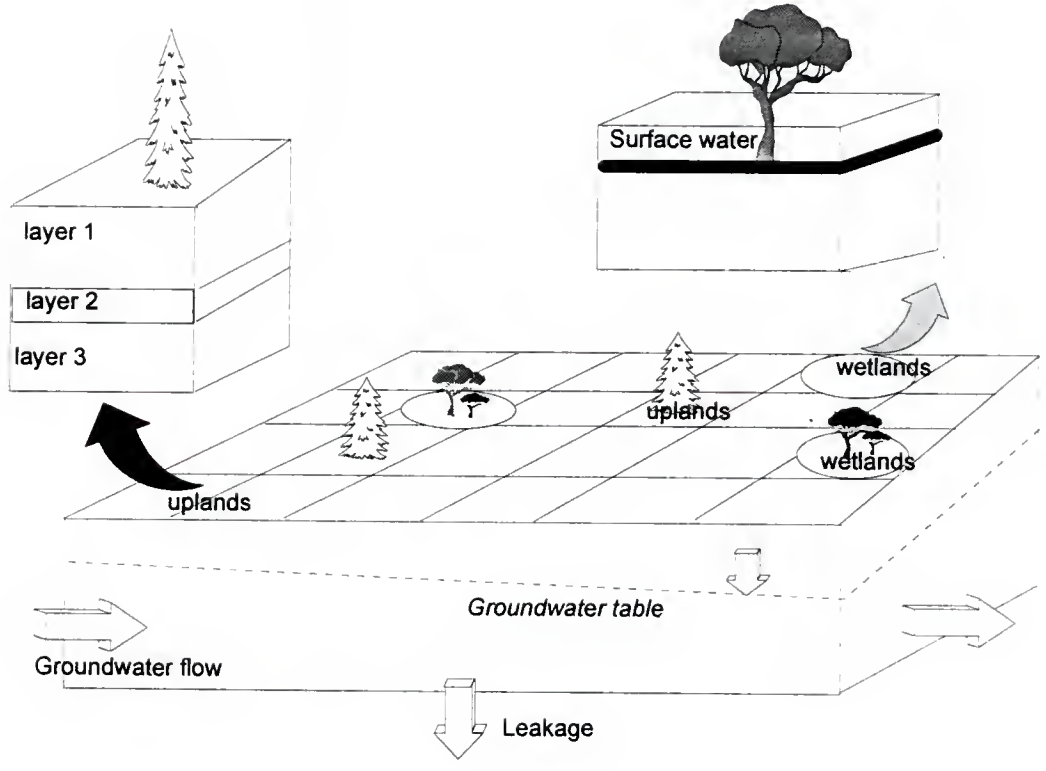


Figure 5.1. Structure of the FLATWOODS model showing the grid system and modeling units of pine uplands and cypress wetlands.

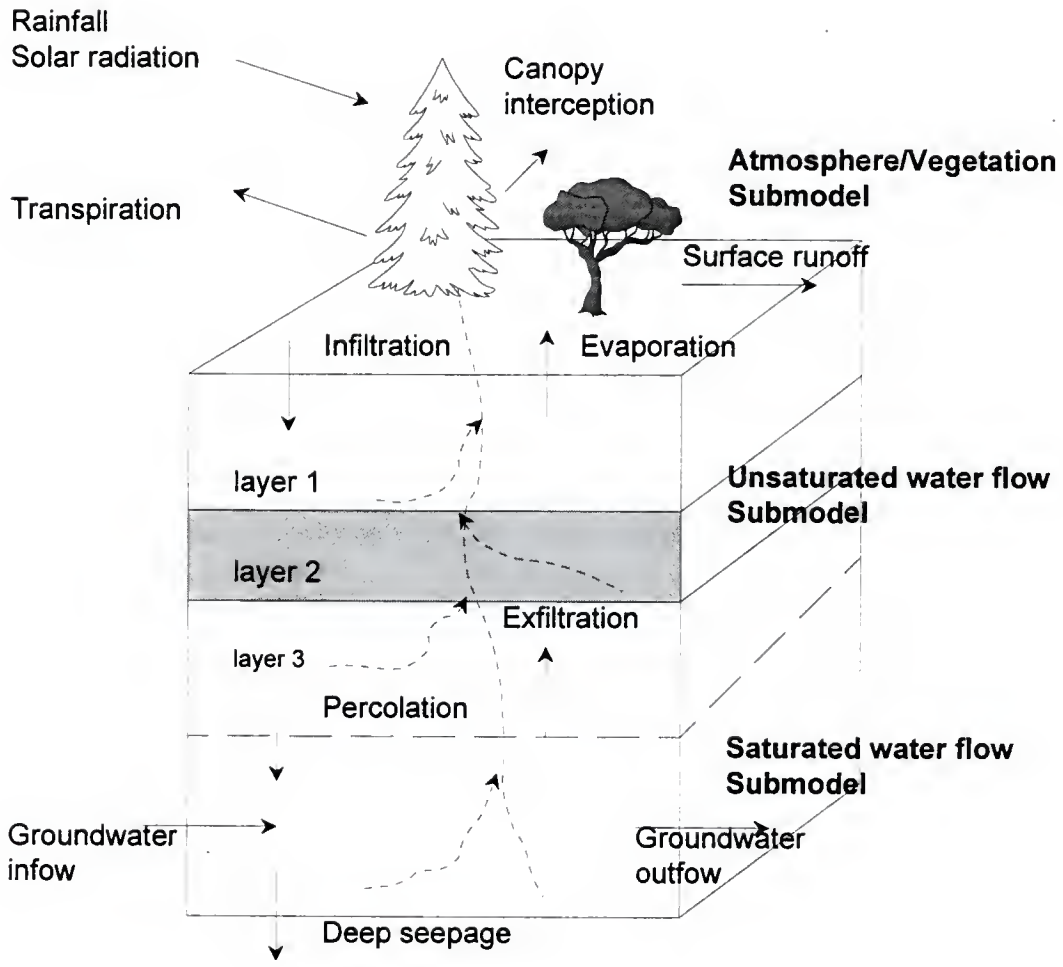


Figure 5.2. Hydrologic components of the three submodels in the FLATWOODS model.

(PET), an index of the maximum water loss for given atmospheric and land cover conditions. This equation, however, needs several climatic variables that are not easily derived from the present research site. Consequently, the method by Hamon (1963) was adopted to estimate PET with only daily temperature as a requirement. Evaporation of intercepted water on forest canopies has first demand on PET. Residual potential evapotranspiration (RET) is the difference between PET and evaporation from plant surfaces (intercepted rainfall on canopies). Actual evaporation (AE) from soil/water surfaces is dependent on atmospheric demand, soil water conditions and is affected by forest canopy shading. Actual transpiration (AT), which involves physical and physiological processes, is the most difficult component to model. In the FLATWOODS model, AT extracted from each of the soil layer is a function of possible realized transpiration (PRT), soil water conditions, and root density. The concept of PRT is defined as the maximum transpiration that a crop can have for a certain atmospheric condition and LAI. PRT is a function of the residual potential evapotranspiration (RET), and stage of plant development indicated by LAI and root density.

2. The unsaturated water flow submodel.

Due to the high infiltration rate of sandy soils, rainfall that is not intercepted by forest canopies infiltrates rapidly into the soil zones without any overland flow loss. A maximum of three unsaturated soil layers have been used to simulate subsurface unsaturated water flow. The first layer (0-40 cm) represents the A horizon where most plant roots reside. The second layer (40-65 cm) represents the spodic horizon (B_h) where soil properties are distinct from the top layer. The third layer ranges from the 65-cm depth to the water table. The thickness in each layer varies throughout the simulation depending on water table depth. For

example, if the water table comes to the soil surface, the whole soil profile is saturated and the number of unsaturated soil layers becomes zero; if the water table depth is greater than 40 cm but less than 65 cm, two unsaturated soil layers are stipulated with the first layer as 0-40 cm and the second as 40 cm to the water table level. Drainage representing downward unsaturated water flow from an upper layer to a lower layer is estimated by Darcy's equation assuming unit total potential gradient. Upward water flux represents water flow from a lower layer to an upper layer, driven by the water potential gradients induced by ET. This component is calculated in direct proportion to the ET flux in the layer. While evaporation from the soil surface takes place only from the first layer, plant roots extract water from all three unsaturated layers and the saturated zone. Soil moisture content is routed with the water balance in each layer. For some areas, such as wetlands, the soil profile may be fully saturated during part or all of the year. Percolation from the bottom of the third layer of the unsaturated zone becomes the input (source) to the underlying saturated subsystem.

3. The saturated water flow submodel

The base of the unsaturated zone becomes the upper boundary of the saturated zone. The bottom of the saturated zone has been set at the top of the clay layer about 2-3 m deep and which has a low conductivity $< 10^{-3}$ m/day. Below this flow-restricting clay layer, which may be discontinuous in extent, often lies another intermediate aquifer composed of sands and sandy loams. Vertical flow (leakage) through the bottom of the saturated zone is estimated using an empirical function. Within the saturated zone of the submodel, water moves horizontally from one cell to the surrounding four cells governed by a 2-D groundwater flow model with Dupuit assumptions (Bras, 1990). The two important

parameters, specific yield and hydraulic conductivity in the groundwater flow equation, are not constant but vary depending on the position of the water table in the soil profile. A source of the submodel is water percolation from the unsaturated zone. A sink of the groundwater flow model includes ET extracted from the aquifer, exfiltration (upward flux) from the saturated zone to the unsaturated zone, and/or surface flow from those cells where the water table is above a critical elevation.

Governing Equations

Potential evapotranspiration

Potential evapotranspiration (PET), as an index of the upper limit of the evaporative power of the site, is estimated using a method by Hamon (1963).

$$PET = 0.1651 \times DAYL \times RHOSAT \times KPEC \qquad (5.1)$$

where,

DAYL = time from sunrise to sunset in multiples of 12 hours, calculated from date, latitude, slope and aspect of the watershed using Swift's (1976) procedure;

RHOSAT = saturated vapor density (g/m3) at the daily mean temperature (TEMP)(°C);

$= 216.7 \times ESAT / (TEMP + 273.3)$;

ESAT = saturated vapor pressure (mb)

$= 6.108 \times \exp [17.26939 \times TEMP/(TEMP + 237.3)]$;

KPEC = correction coefficient to adjust PET calculated using Hamon's method to realistic values. Reported values for KPEC ranged from 1.0 (Hubbard Brook, New Hampshire) to 1.2 (Coweeta, North Carolina). For Gainesville, Florida, a value of 1.3 proved to be

appropriate.

Rainfall interception

$$I_p = a + b \times P \quad (5.2)$$

where,

I_p = rainfall interception (mm/day);

P = gross daily rainfall (mm/day);

a, and b = forest parameters characterized by the forest LAI fitted from throughfall measurements.

The maximum interception or canopy storage capacity C_{max} in mm was introduced to make the empirical model (Equation. 5.2) more realistic. Canopy storage capacity was determined by assuming that canopy saturation was approximated by a 1.0-mm-thick water film over the foliage surfaces:

$$C_s = 1.0 \times LAI \quad (5.3)$$

Then, available canopy storage for rainfall interception (ASIN) = C_s + PET - SIN

where,

SIN = water stored on the forest canopy the day before the simulation date (mm);

$ASIN = C_s$ If PET > SIN

$I_p = a+b \times P$ If I_p < ASIN

I_p = ASIN If I_p > ASIN

$I_p = 0$ If ASIN = 0

The throughfall component (T_p) represents rainfall that passes through all vegetation layers and becomes available for infiltration into the ground.

$T_p = P - I_p$

Variation of the leaf area index (LAI) of cypress wetlands and slash pine plantations as a function of Julian day (t) are represented by the following equations. For the slash pine forest at the GNF site, the LAI is modeled as:

$$LAI(t) = 2.25 + 0.25 \times \sin(\frac{2\pi}{365}t + 1.1\pi) \quad (5.4)$$

Data for developing this formula were published by Riekerk et al. (1995).

Mature slash pine plantations are assumed to have a maximum LAI and transpiration rate.

$$MLAI(t) = 5.0 + 0.9 \times \sin(\frac{1.8\pi}{365}t + 0.9\pi) \quad (5.5)$$

Data for developing this formula were published by Gholz et al. (1991).

For the cypress wetlands at the research site (data from Riekerk et al., 1995):

$LAI(t) = 1.2$ $\quad t < 60$

$LAI(t) = 1.2 + (3.93 - 1.20)/(121 - 61)\, t = 1.2 + 0.0455\, t$ $\quad 60 < t < 121$

For the rest of the year, i.e. t>121:

$$LAI(t) = 1.5 + 4.4 \times \sin(\frac{1.1\pi}{365}t + 1.9\pi)$$

Cypress forests at the sites of the present study are assumed to be in the mature stage with the maximum leaf area index.

Evaporation from the soil surface

As outlined by Hillel (1980), three phases of the soil evaporation process exist for an initially wet soil drying down, but without a water table near the surface. However, when a near-surface water table exists, it controls the three evaporation processes to a large degree (Phillips, 1987). A steady state may develop and continue for a significant time. During this period, the soil moisture content at the top layer does not change much but the water table may drop significantly while replenishing soil moisture to the unsaturated zone (Gardner, 1958).

Solar energy is first consumed by evaporation of the rain water intercepted on the forest canopy before reaching the ground. Residual potential evapotranspiration (RPET) has been defined as the difference between PET and SIN. Evaporation from the soil surface is also reduced by forest canopy shading (McCarthy, 1992). Field data suggest that evaporation from a floating pan under the cypress wetland canopies of the study area was only about 30% of the standard pan evaporation (Riekerk et al., 1995).

$$PE = RPET \times \exp [-KE1 \times LAI(t)] \qquad (5.6)$$

where,

PE = potential evaporation (mm/day);

RPET = residual potential evapotranspiration (mm/day) = PET - SIN ;

LAI(t) = leaf area index on Julian day t;

KE1 = soil evaporation reduction coefficient.

Actual evaporation (AE) is modeled as a function of water table depth (WDEP) in two phases:

Phase 1: atmosphere dependent

$AE = PE$ if WDEP < 35 cm

phase 2: water table dependent

$AE = PE \times KEC \times [(100\text{-}h)/(100\text{-}35)]^{KE2}$ if 35 cm < WDEP < 100 cm

phase 3: no evaporation

$AE = 0.$ if WDEP > 100 cm

Where, KEC and KE2 are parameters.

Transpiration

Assumptions were made that transpiration will not be limited as long as the soil moisture content is higher than the field capacity and plant roots of both cypress and slash pine plantations do not stop extracting water when under inundation (Fisher and Stone, 1990). Potential transpiration (PT) is the difference between RPET and AE representing the maximum available energy for plant transpiration.

$PT = RPET - AE$

$$PRT = PT \times \frac{LAI(t)}{MLAI(t)} \times \frac{TRD}{MTRD} \tag{5.7}$$

where,

PRT = potential realized transpiration as explained in the previous section (mm/day);

TRD = root density of the entire soil profile of the modeled forest (m/m2);

MTRD = root density when the forest reaches an age with maximum transpiration capacity (m/m2).

The actual transpiration (AT_i) from each of the three layers depends on PRT, root density, and the soil moisture content of each layer:

$AT = \sum AT_i$ $\quad i = 1, 2, 3$

$AT_i = WEIGHT(i) \times PRT \times F_i$

$WEIGHT\ (i) = RD_i / TRD$

where, RD_i = root density of the layer i (m/m2);

$WEIGHT_i$ = weighing factor that distributes the total transpiration among the soil layers according to the root density distribution.

and,

$F_i = 1.0$ $\quad$ if $\theta_i >= \theta_{i,f}$,

$$F_i = 1 - \left(\frac{\theta_{i,f} - \theta_i}{\theta_{i,f} - \theta_{i,w}}\right)^{\frac{CT}{PRT}}$$ $\quad$ if $\theta_i < \theta_{i,f}$

F_i = coefficient to reflect the effects of soil moisture content, ranging from 0-1;

CT = empirical parameter;

θ_i = soil moisture content in layer i;

$\theta_{i,f}$ = soil moisture content at field capacity in layer i;

$\theta_{i,w}$ = soil moisture content at the wilting point in the layer i.

Water flow in the unsaturated zone

Water flow in the unsaturated zone is essentially vertical due to the low topographical gradient of flatwoods. Lateral unsaturated hydraulic gradients may increase at the pond

margin areas, where surface water/groundwater interactions take place. Unsaturated water movement can be described by a combination of Richard's continuity equation and Darcy's law. This approach has been widely used by soil physicists who are mostly interested in the water/solute transport in porous media at small spatial scales (soil columns) and processes of short periods (days) (Freeze, 1971). Limitations for the use of a completely physical water flow model have been documented by Anderson and Woessner (1992). These limitations of a general physical flow model for large-scale flatwoods systems include: (1) numerical solutions are complicated, requiring large computer memory and CPU time due to the small time step and small nodal spacing; and (2) soil water characteristic curves and other model input data are often not readily available. These two limiting factors are especially true for distributed models. Frind and Verge (1978) suggested that it might not be feasible to model field-scale problems with a general subsurface model. In contrast, a one-dimensional unsaturated soil column model linked to a two- or three-dimensional saturated water flow model may be a better alternative (Pikul et al., 1974).

The model built for the present study compromises physical complexity, data requirements, and model accuracy. Since our objective was to investigate seasonal hydrologic dynamics for small watersheds, a physical model for ground water flow coupled with a simpler model for the unsaturated water flow was constructed. This approach greatly reduced CPU time but provided moderate accuracy for ground water flow modeling.

The procedure for soil moisture routing and unsaturated water flow is based on the soil water balance:

$$\theta_i^{t+1} = \theta_i^t + (D_{i-1}^t - E_i^t - T_i^t - D_i^t)\times\Delta t \tag{5.8}$$

where,

θ_i^{t+1} = unknown water content expressed in the layer i, day t+1 (cm);

θ_i^t = known water content at the layer i, day t (cm);

D_{i-1}^t = drainage rate at the layer i-1, day t; if layer i is the top layer, D_{i-1}^t = infiltration (cm/day);

D_i^t = drainage rate at layer i, day t (cm/day);

E_i^t = if the layer i is the first layer, it represents the evaporation rate from layer 1. Otherwise, it is the upward flux from the layer i to i-1 due to water potential differences between the two layers (cm/day);

T_i^t = transpiration rate from the layer i (cm/day);

Δt = time step (one day).

The expression for the drainage rate (D_i) may be derived from Darcy's law (Eq. 5.9), where h is the matric potential uniquely related to the water content θ:

$$q = -K(h)\frac{\partial H}{\partial z} = -K(h)(\frac{\partial h}{\partial z}+1) = -K(h) \tag{5.9}$$

Assuming the water matric potential is uniform for each layer, then $\partial h/\partial z = 0$. So, the drainage rate or percolation rate can be approximated as unsaturated hydraulic conductivity K(h). The flux of q can also be approximated by K(h) corrected by a coefficient of 1.5 (P. S. Rao, personal communication).

The model by Van Genuchten (1980) for the relation between h and K(h) for sandy

soils has been widely used (Selim et al., 1976; Hansen and Mansell, 1986; Phillips, 1987; Fares, 1993):

$$K(h) = K_s[1+(\alpha h)^n]^{-\frac{m}{2}}[1-(\alpha h)^{n-1}(1+(\alpha h)^n)^{-m}]^2 \quad (5.10)$$

where,

K_s = saturated hydraulic conductivity (cm/day);

m = 1-1/n, where n is a constant determined by fitting the soil moisture release curve;

α = constant determined from the soil moisture release curve;

h = matric potential head (cm).

The relation between the volumetric soil moisture content (θ) and matric potential (h) was also derived by Van Genuchten (1980) as equation (5.11):

$$S_e = \frac{\theta-\theta_r}{\theta_s-\theta_r} = [1+(\alpha h)^n]^{-m} \quad (5.11)$$

where,

S_e = effective degree of water saturation (%);

θ = volumetric soil moisture content (%);

θ_s = saturated soil moisture content (%);

θ_r = residual soil moisture content at the wilting point (%).

Combining the two equations gives:

$$D(\theta) = K(\theta) = K_s S_e^{1/2}[1-S_e(S_e^{-1/m}-1)^m]^2 \quad (5.12)$$

For a specific water content θ, a corresponding drainage rate, $D(\theta)$, can be found from Equation 5.12.

The upward flux, E_i^t or exfiltration rate in layer i is controlled by the evaporation at the soil surface and the transpiration from the layer i and those above it. In the present model, E_i^t is modeled by:

$E_i^t = CET \times T_i^t$

where,

CET = model parameter;

T_i^t = transpiration from the layer i.

Shallow groundwater flow

In flatwoods uplands, surface flow rarely occurs unless the water table rises to the soil surface. Groundwater flow dominates the soil system during most of the time. In wetlands, however, surface water is periodically present and the overland flow may link otherwise isolated wetlands. Field studies indicate that different cypress wetlands show different hydrologic characteristics. Most of the wetlands are flow-through types for both groundwater and surface flow. The groundwater enters from one side of a wetland and discharges from another side into the surrounding uplands. Reversal of groundwater flow was also documented during the dry season in some wetlands. Hence, the flow pathways in flatwoods are mixed and the general governing equations for saturated water flow must include both the groundwater flow and the surface flow components.

The water table aquifers at the study sites were hydrologically isolated from deep

aquifers due to the underlaying clay layer. Experimental studies suggested some water leakage from the top aquifer systems to the lower "sandwiched confined aquifers". The 2-D model for the groundwater flow in an unconfined aquifer was used to represent the saturated flow system and constitutes the core of the FLATWOODS model.

$$\frac{\partial\left(K_x h \frac{\partial h}{\partial X}\right)}{\partial X} + \frac{\partial\left(K_y h \frac{\partial h}{\partial Y}\right)}{\partial Y} - W = S_y \frac{\partial h}{\partial t} \qquad (5.13)$$

where,

K_x, K_y = hydraulic conductivity along the horizontal X axis and Y axis, calculated as the average of the aquifer thickness and varying with water table elevation (m/day);

h = hydraulic head (m);

W = water flux representing sources (e.g., drainage from unsaturated layers) and sinks (e.g., ET, surface runoff, leakage)(m^3/day);

S_y = specific yield of the aquifer; it is not a constant, but varies with water table elevation;

S_y = 1.0 If the hydraulic head elevation > soil surface elevation;

S_y = f (h) otherwise;

t = time (day).

Because Equation 5.13 is a nonlinear differential equation, a finite difference method was used to solve for the head h(x, y, t) variable. The discrete form of the above equation was described by the following equations:

$$C_{j-1,j}h^m_{i,j-1} + C_{j,j+1}h^m_{i,j+1} + C_{i-1,i}h^m_{i-1,j} + C_{i,i+1}h^m_{i+1,j} + (- C_{j-1,j} - C_{j,j+1} - C_{i-1,i} - C_{i,i+1} + HCOF_{i,j}) h^m_{i,j} = RHS_{i,j}$$

where,

i, j = identifier of the row and the column of the grid system, respectively;

$C_{j-1,j}$ = conductance between cell (i, j) and cell (i, j-1)

$= K_{j-1,j}$ dy dz/dx;

$HCOF_{i,j}$ = Head COeFficient = $-Sy_{i,j}$ dxdy/($t_m - t_{m-1}$);

$RHS_{i,j}$ = Right Hand Side term

$= - S^m_{i,j,n} - Sy_{i,j}$ dx dy $h^{m-1}_{i,j}$ /($t_m - t_{m-1}$);

$S^m_{i,j,n}$ = the n^{th} source (positive) or sink (negative) term for the cell (i, j) with a unit of m^3/day;

dx, dy = cell width and length;

dz = aquifer thickness;

m = time indicator;

$h^{m-1}_{i,j}$ = head of the cell (i, j) of the last time step (known);

$h^m_{i,j}$ = head of the present time step (unknown).

To solve the above equation, boundary conditions and initial conditions must be first specified. For a closed system, such as a watershed, the boundary conditions at watershed ridges can be set as a no-flow boundary (special Neumann boundary). For a plot without lateral physical boundaries, a constant gradient boundary (Neumann boundary) may be appropriate, especially for flat homogeneous terrain. Initial conditions included spatial distributions of the soil moisture content and corresponding hydraulic head for each cell. The initial soil moisture content was automatically estimated by the model through a generalized relationship between the water table depth and the overlaying soil moisture content.

Linkage between the unsaturated flow (drainage, source term) and ET (sink term) submodels was represented by the term W in the groundwater flow model (Equation 5.3). When the water table head h(x, y, t) was higher than a specified critical topographical elevation, surface flow occurred.

Because Equation 5.13 is only applicable to the groundwater flow in porous media, problems may arise when it is applied in the wetland-upland landscape under certain circumstances.

Case 1: surface water-ground water interaction

This case can be found at the margins of a cypress pond when the area of a grid cell used in the model is smaller than the pond area. Under this condition, Darcy's law still holds for water flow between adjacent cells but the specific yield of the cell in the wetland may be set to 1.0.

Case 2: surface water-surface water

This case may be encountered when the area of two adjacent grid cells in the model is smaller than the pond area. In this case, the surface flow dominates the entire pond system and the equation is not valid. However, an approximation is justified by setting $S_y = 1.0$ and Ks = 50 m/day (Walters and Bengtsson, 1994).

Surface flow

The surface flow may occur from a grid cell under extreme wet conditions when the soil profile is saturated and the water table elevation is higher than the specified critical elevation. This situation happened in both wetlands and uplands at the study sites. The

critical elevation is defined as the surface elevation above which overland flow occurs. For uplands, it was the topographical elevation. For cells in cypress ponds, the critical elevation was the minimum elevation of the palmetto line at the flow outlet.

In the FLATWOODS model, the surface runoff leaving a flooded cell is modeled proportionally to the total saturated area of the entire watershed. The total daily runoff from the watershed was first simulated as a function of the average water table level, then equally distributed to each cell where overland flow occurred.

$S_f(t) = K1 \times \exp [h(t) - K3]^{K2}$ If $h(t) \geq CWT$

$S_f(t) = K1 \times [h(t)-K3]/[CWT-K3]$ If $K3 < h(t) < CWT$

$S_f(t) = 0$ Otherwise

where,

$S_f(t)$ = daily total surface runoff from the entire watershed (mm/day);

K1, K2 = parameters calibrated by measured data;

h(t) = average water table elevation (m);

CWT = critical water table elevation (m)

= Average Topographical Elevation of the watershed - Critical Soil Depth = ATOPO - CSD;

CSD = the soil depth above which the runoff occurs at the outlet of the watershed (m);

K3 = the water table elevation below which no runoff occurs from the entire watershed (m);

Surface runoff from each flooded cell, a sink term in Equation 5.15, was modeled by:

$$SC_i(t) = S_f(t) \times A_i / TSA \quad (5.14)$$

where,

A_i = the surface area of the cell (m^2);

TSA(t) = total saturated area (variable source area) (m^2).

Deep seepage

The deep seepage component, one of the sink terms in Equation 5.15, is defined as the water that leaks from the bottom of the water table aquifer to the lower and sometimes artesian aquifer. This can be calculated by the Darcian method if the water table levels in both aquifers and the hydraulic conductivity of the restricting clay layer are known. Unfortunately, due to the complexity of field conditions, it was difficult to model the water table dynamics of the two aquifers simultaneously. For the present study, we used a simplified method to simulate the deep seepage from each cell. The deep seepage loss was assumed to follow a power function of the saturated thickness of the surficial aquifer:

$$DS(t) = K_d \times [h(t) - BOT]^2 \quad (5.15)$$

Where,

K_d = a model parameter;

BOT = bottom elevation of the surficial aquifer of a cell (m).

Model Inputs and Outputs

Model Inputs

Input requirements to run the model are listed in Table 5.1.

Model Outputs

Model outputs from the model are listed in Table 5.2.

Table 5.1. A list of model inputs required to run the FLATWOODS model.

Model Inputs	Variables/Parameters
Climatic data	Daily rainfall; Daily average air temperature; Latitude of the study site; Correction factor for calculating potential evapotranspiration by Hamon's method; Empirical function for rainfall interception.
Watershed configurations	Grid size, width and length, area; Land use type (cypress wetland, pine upland, harvested wetland, and harvested upland); Topographical elevation and bottom elevation of each cell; The critical elevation of each cell; Boundary condition identifiers 0 - no flow 1 - variable hydraulic head -1 - constant gradient boundary
Soil parameters	Soil moisture characteristic curves by Van Genuchten's method; Saturated hydraulic conductivity of each soil layer in each cell; Specific yield of each soil layer in each cell; Relationships between the soil moisture content and the water table level for different soil layers; Empirical parameters used in the ET submodels (KE1, KE2, CET, CT1 and CT2); Empirical parameters used to calculate surface runoff and deep seepage (K1, K2, K3, CSD, K_d).
Vegetation parameters	Leaf area index functions for each crop type and its change with time (day); Root density for each crop type in each soil layer.
Initial conditions	Hydraulic head (water table elevation) in each cell throughout the watershed at the beginning of a simulation.

Table 5.2. A list of model outputs from the FLATWOODS model.

Daily water table elevation in each grid cell and its average over the entire watershed;
Daily rainfall interception, evaporation, and transpiration from each cell;
Daily total surface runoff and groundwater flow across the boundaries from the entire watershed;
Daily water drainage (percolation) from the unsaturated zone to the saturated zone;
Daily soil water storage in each soil layer;
Daily deep seepage from the surficial aquifer to the underlying second aquifer;
Statistical analysis on model performance.

Model Calibration and Verification

Model Calibration and Verification Schemes

A predictive computer simulation model is valid only after it has been tested against appropriate experimental data. The testing processes involve model calibration and model verification procedures. The model calibration is often needed because empiricism exists for most hydrologic simulation models. For a lumped simulation model, effective parameters have to be identified through the model calibration to represent the average properties of a watershed. For a distributed model, such as the FLATWOODS model, detailed information of soil and plant covers for each grid cell is not available in most cases, and some degree of homogeneity has to be assumed. Model calibration involves fitting measured data to simulated responses within some range of accuracy by adjusting the values

of process parameters (Fleming, 1975). Once the model is calibrated, a different data set is used to test its performance again. This process is called model verification.

The FLATWOODS model was calibrated and verified with hydrologic data collected from two study sites, the Gator Nationals Forest (GNF) and the Bradford Forest (Table 5.3). Although the FLATWOODS model had the potential to use spatially distributed soil and vegetation parameters, it was not realistic to give a different value for each cell. So, the same values for the leaf area index and soil physical parameters of each soil layer for each land type were used in the simulation, but the surface elevation of each cell was interpolated from the topographic map. The bottom elevation of each cell was set as the surface elevation

Table 5.3. Data sources for the model calibration and verification.

Research site		Calibration	Verification
Gator Nationals Forest	Pre-treatment	Apr. 6, 1992 - Dec. 31, 1993 Data: Average groundwater table level	Jan. 1, 1994 - May 31, 1994 Data: Average groundwater table level
	Post-treatment	Jun. 1, 1994 - Dec. 31, 1994 Data: Average groundwater table level	Jan. 1, 1995 - May 31, 1995 Data: Average groundwater table level
Bradford Forest (No treatment data)		Jan. 1, 1978 - Dec. 31, 1982 Data: runoff, groundwater table levels from five wells	Jan. 1, 1983 - Dec. 31, 1992 Data: runoff

minus a uniform thickness over the entire watershed. Soil parameters for the soil moisture

characteristic curves measured by Phillips (1987) for a nearby site were not adjusted.

A combination of statistical and graphical methods was employed to quantify differences between simulated (S_i) and measured (M_i) variable series. The Pearson correlation coefficient and the objective function (index of disagreement) were used to evaluate the model performance and obtain optimum parameters.

Pearson Correlation Coefficient (PCC):

$$PCC = \frac{n\sum_{i=1}^{N} M_i S_i - \sum_{i=1}^{N} M_i \sum_{i=1}^{N} S_i}{\sqrt{n\sum_{i=1}^{N} M_i^2 - \left(\sum_{i=1}^{N} M_i\right)^2} * \sqrt{n\sum_{i=1}^{N} S_i^2 - \left(\sum_{i=1}^{N} S_i\right)^2}} \qquad (5.16)$$

Objective function F:

$$F = \sum_{i=1}^{N} (S_i - M_i)^2 \qquad (5.17)$$

Model Calibration and Verification Results

Gator Nationals Forest (GNF) site

Pre-treatment. Landuse, topography, and modeling units have been presented in Figure 5.3. More than 130 shallow wells (< 1 m) were installed at the GNF site and the water table level in each well has been measured biweekly since April 1992 (Comerford, personal communication). The arithmetic average of all water table elevations from each

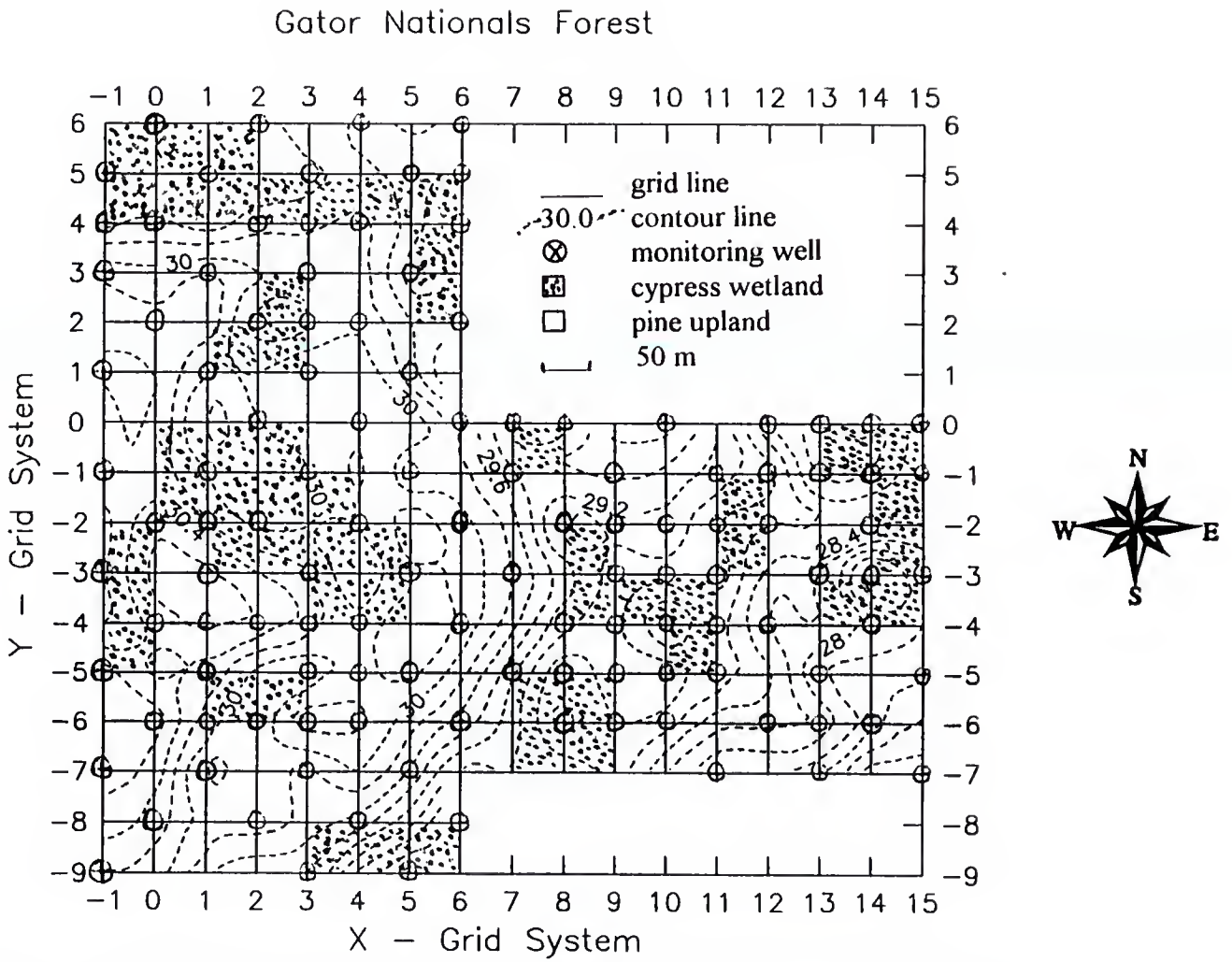


Figure 5.3. Physical information of the modeling units of the Gator Nationals Forest site.

measurement was used for the model calibration. The model was first calibrated with water table data for the GNF site for the wet year of 1992, which had a 170-mm surplus of rainfall compared to normal years (rainfall =1330 mm). Satisfactory results were obtained for this year. However, when a verification effort was tried using data collected from the dry year 1993, the model significantly overestimated the water table level using the calibrated parameters of 1992. This problem was probably caused by underestimation of the depth of the restricting clay layer. As a result, the restricting depth was changed from 2.0 m to 3.5 m, and a better fit was achieved for the year 1993. The dry year of 1993 had a rainfall deficit of more than 230 mm as compared to a normal year, and consequently about 6-93% of the observation wells were dry from May to October. However, using both a dry year and a wet year for the model calibration enhanced the generality of the model. The calibration results for the pretreatment period were good and have been presented graphically in Figure 5.4. Model verification with data from January 1, 1994 to May 31, 1994 during the pre-treatment period also showed good model performance. The Pearson Correlation Coefficient was 0.91 and 0.96 for the calibration period and the verification period respectively. Monthly simulation results including runoff, evapotranspiration, percolation, and deep seepage have been summarized in Table 5.4. Predicted daily evapotranspiration (including canopy interception) and runoff during 1992-1994 have been presented in Figure 5.5. Since physical watershed boundaries at the GNF site did not exist, the predicted runoff represents the net runoff (outflow minus inflow) including both the groundwater flow and the surface flow across the constant gradient boundary line.

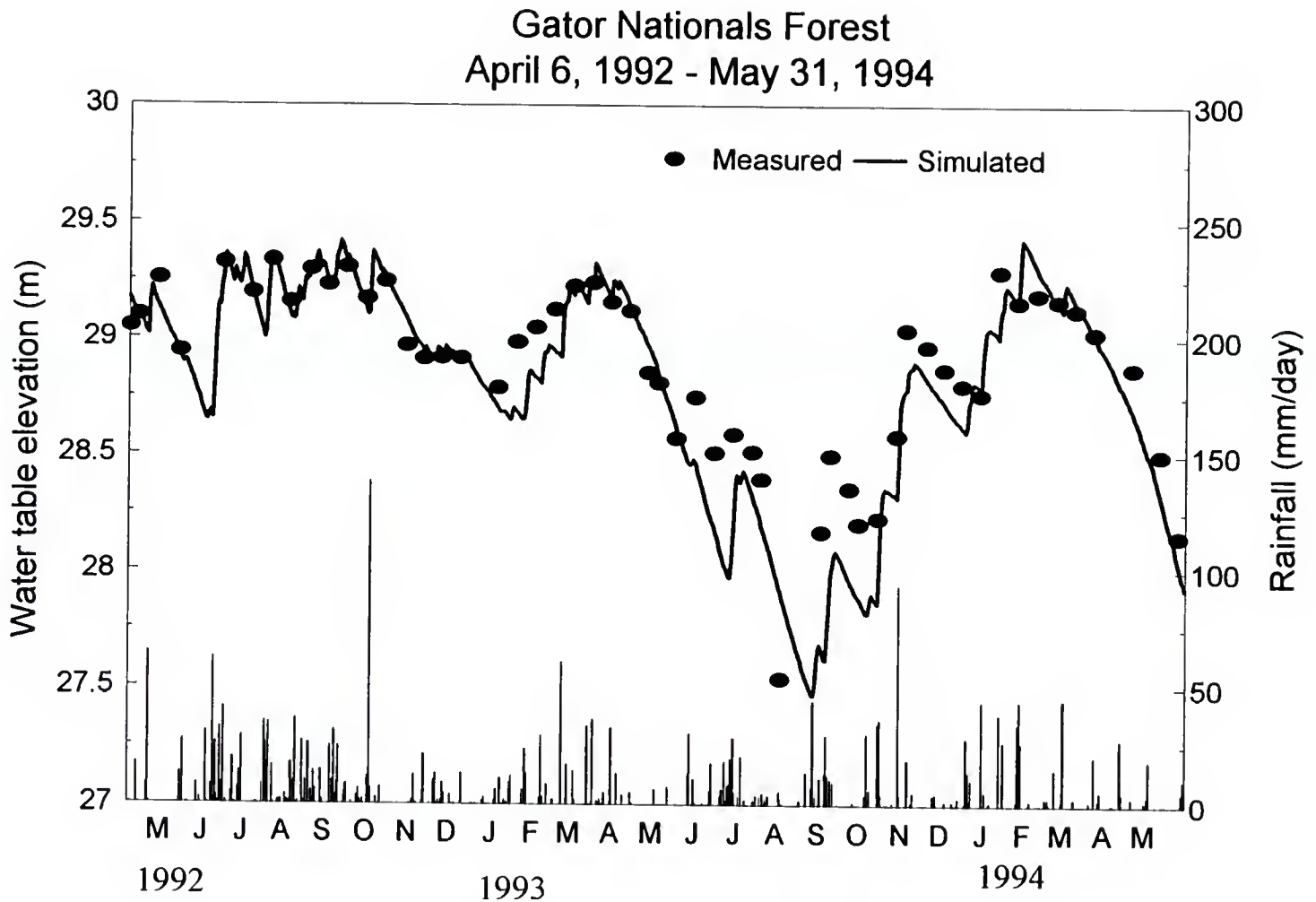


Figure5.4. The FLATWOODS model calibration (April 6 - December 31, 1993) and verification (January 1, 1994 - May 31, 1994) with measured average groundwater table data during the pre-treatment period.

Table 5.4. Simulated results for the calibration and verification period before treatments (1992-1994), Gator Nationals Forest.

	Month	Day	Precipitation (mm)	Runoff (mm)	Avg. Head (m)	E (mm)	T (mm)	E+T (mm)	Inter (mm)	UDrain (mm)	Gflow (mm)	Ds (mm)
Model	4	25	91	6	29.119	23	50	74	9	56	2	5
Calibration	5	31	54	3	28.903	20	72	91	10	3	1	5
	6	30	298	8	29.102	25	77	102	43	171	3	7
	7	31	146	10	29.209	39	79	118	25	80	3	7
1992	8	31	185	12	29.235	30	70	100	35	104	4	8
	9	30	135	12	29.275	28	63	91	25	78	4	8
	10	31	168	11	29.212	21	40	61	11	129	4	7
	11	30	81	3	28.962	14	37	51	17	16	2	6
	12	31	24	2	28.865	12	30	42	5	5	2	6
	Total	270	1181	66	29.097	211	518	729	181	642	24	58
Model	1	31	89	2	28.713	11	32	43	16	30	2	5
Calibration	2	28	124	5	28.972	14	24	38	13	79	3	6
	3	31	129	12	29.229	26	36	62	15	78	4	8
	4	30	23	8	29.111	26	44	70	5	8	3	7
	5	31	58	2	28.664	16	46	62	11	4	2	5
1993	6	30	143	1	28.201	3	85	89	29	22	1	3
	7	31	53	2	28.249	9	99	108	12	19	2	3
	8	31	80	0	27.679	0	54	55	13	10	0	2
	9	30	90	0	27.905	3	76	78	18	29	0	2
	10	31	215	2	28.118	5	54	59	21	94	2	3
	11	30	38	6	28.82	16	38	54	8	19	6	5
	12	31	62	4	28.702	8	21	29	11	22	4	5
	Total	365	1103	42	28.527	139	608	747	170	413	28	52
Model	1	31	223	11	29.134	16	22	37	20	170	5	7
Verification	2	28	24	10	29.261	29	27	56	5	0	2	7
	3	31	80	8	29.094	28	38	67	9	30	3	7
1994	4	30	37	2	28.753	14	62	76	6	1	2	5
	5	31	41	1	28.239	2	61	63	9	0	1	3
	Total	151	404	30	28.89	89	209	298	48	200	12	28

Note: E = Evaporation from the soil/water surface; T = transpiration from plants;
UDrain = water drained from the unsaturated zone to the saturated zone; Ds = vertical seepage from the underlaying clay layer.

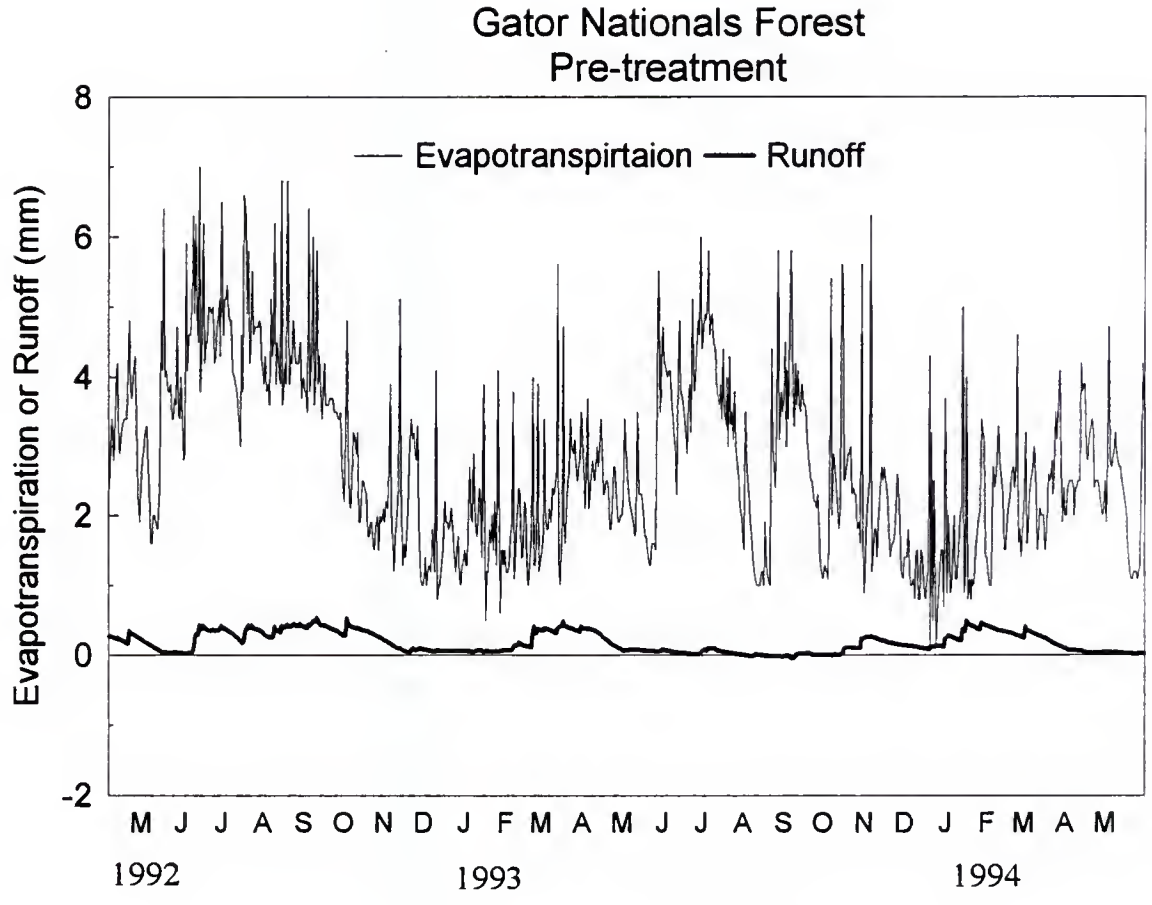


Figure 5.5. Simulated daily runoff and evapotranspiration from the Gator Nationals Forest site during model calibration and verification periods under the pre-treatment condition.

Post-treatment. The harvesting treatments were imposed from April 5 to May 31, 1994, followed by the double bedding during the fall of 1994. The southeast block was totally clear-cut, including the cypress wetlands, but only the wetlands were clear-cut in the northwest block of the research area. The harvested upland areas were planted with slash pine seedlings in January of 1995 and the cypress wetlands left for natural regeneration. Apparently, the most significant effect of the forest harvesting on model parameters was the reduction of the leaf area index. The leaf area index was assumed to be reduced to 0.5 for harvested wetlands and 0.1 for harvested uplands. Soil structure of the first layer also might have been altered due to compaction by the mechanical operations, but the change presumably was minor. Under these assumptions, the model was verified with post-treatment data from June 1, 1994 to May 31, 1995 (Figure 5.6). Obviously, the model significantly over-predicted the groundwater table elevation during the post-treatment period. Discrepancies were possibly caused by: (1) the evapotranspiration algorithms did not describe adequately the physical evaporation processes of the harvested areas; and (2) the management practices included bedding which might have changed the parameters for the soil moisture (porosity) and surface flow routing procedures. The model had to be recalibrated in order to determine the extent of the changes of the affected parameters due to the site disturbance. The model was calibrated again with post-treatment data collected during June 1 - December 31, 1994. To obtain higher calibration accuracy, the simulated water tables were compared against the measured water tables for the NW block (wetlands harvest only), the SW block (control, no harvest) and the SE block (wetlands and uplands harvest) separately (Figure 5.7). The model under-predicted the water table elevation for the

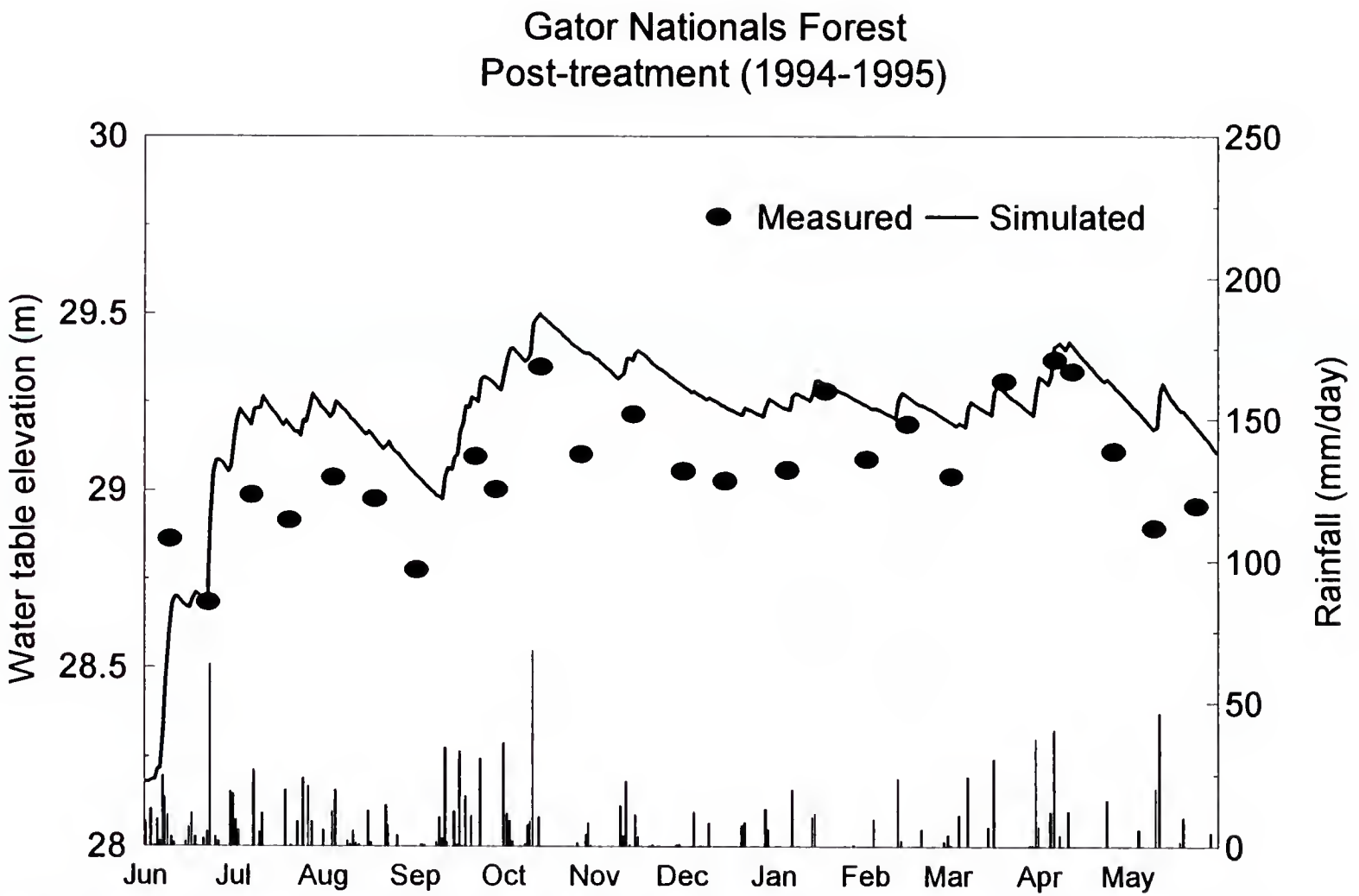


Figure 5.6. Model verification results (June 1, 1994 - May 31, 1995) with post-treatment data (after harvesting) using calibrated parameters of the pre-treatment period, showing an over-prediction of the water table level.

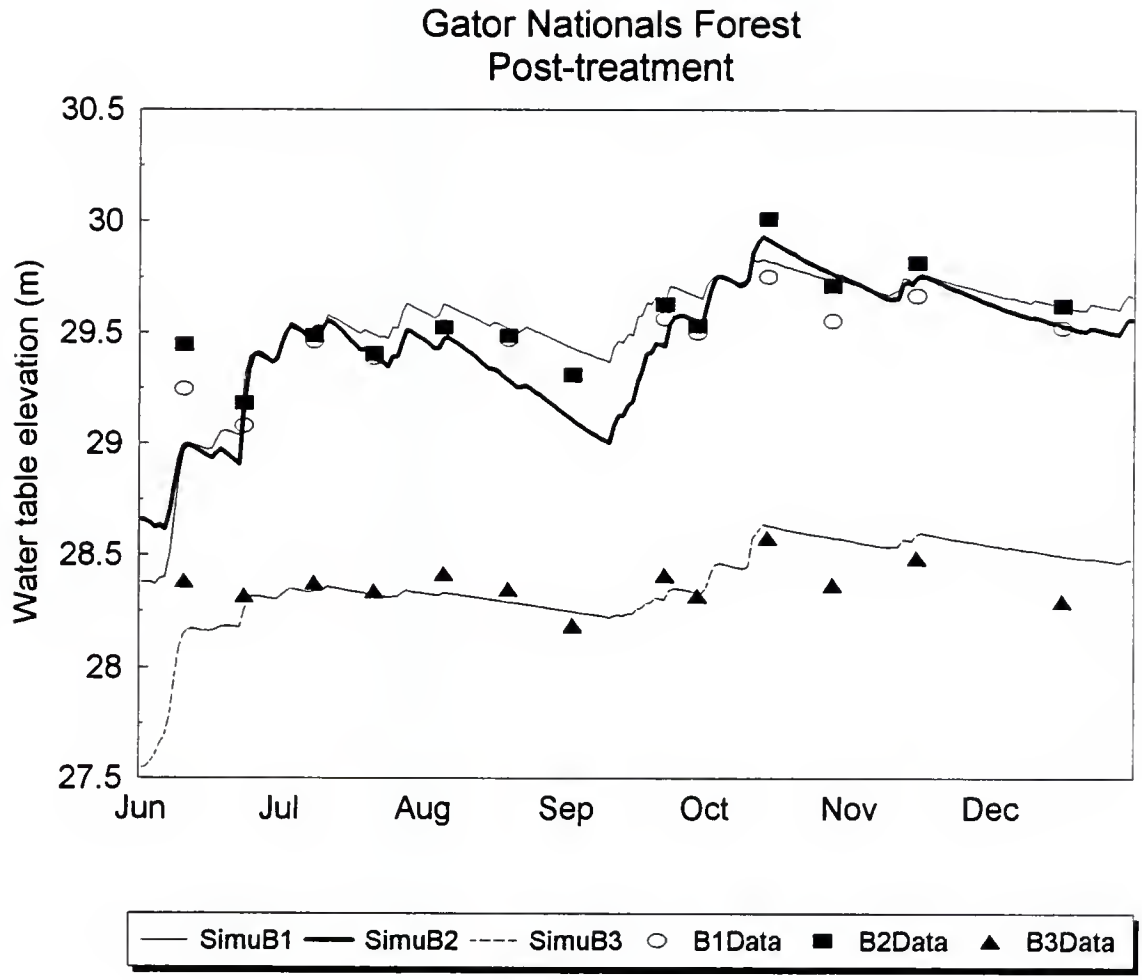


Figure 5.7. The FLATWOODS model calibration with measured groundwater table data from three separate treatment blocks during June 1 - December 31, 1994. The NW block (B1), SW block (B2) and SE block (B3) represent wetlands clear-cut, control, and wetlands and uplands clear-cut treatment respectively.

first measurement in June for all three blocks, but performed reasonably well in other months. The model verification for the post treatment period was performed with average groundwater table elevation data from January 1 to May 31, 1995 (Figure 5.8). The Pearson Correlation Coefficient was 0.88 and 0.82 for model calibration and verification periods, respectively. The simulation results were satisfactory and have been summarized in Table 5.5. The average evapotranspiration value of the entire watershed during the post-treatment period apparently was lower than during the pre-treatment period, while the net runoff during this period was higher, increasing from 6% to about 10% of the total rainfall (Figure 5.9).

Table 5.6 lists the final calibrated parameter values for the Gator Nationals Forest research site. Most of the final FLATWOODS model parameter values are within the reported ranges (Pratt, 1978; Sun, 1985; Comerford et al., 1994; Sun et al., 1995).

Bradford Forest Watershed

The Control watershed (WS3) at the Bradford Forest site had a long runoff record (1978-1995). However, groundwater table data were discontinuous with more data during the first few years. No spatial water table distribution data were available for this site. Physical information for each modeling unit in this site has been presented in Figure 5.10. The FLATWOODS model was calibrated with runoff data of 5 years (1978-1982). The year of 1978 was a wet year (1453 mm rainfall) while the year of 1981 was a very dry year (916 mm rainfall). Simulated daily runoff was compared to actual measurements at the watershed outlet (Figure 5.11 and Figure 5.12). The simulated average groundwater table was guided

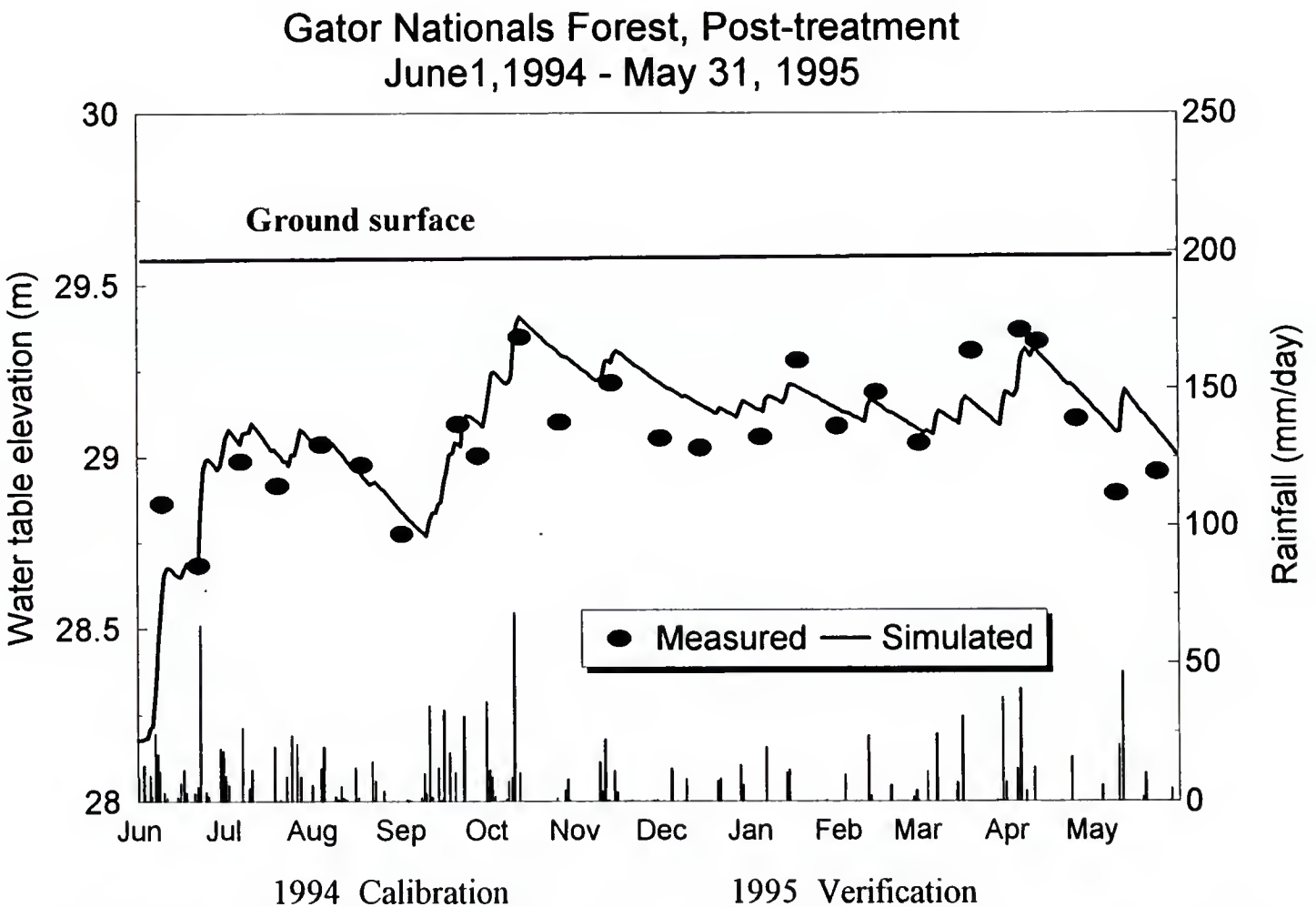


Figure 5.8. Simulated and measured average groundwater tables during the calibration (June 1 - December 31, 1994) and verification (January 1 - May 31, 1995) periods under post-treatment conditions.

Table 5.5. Simulated results for the calibration and verification period after treatments (1994-1995), Gator Nationals Forest.

	Month	Day	Precipitation (mm)	Runoff (mm)	Avg. Head (m)	E (mm)	T (mm)	E+T (mm)	Inter (mm)	UDrain (mm)	Gflow (mm)	Ds (mm)
	6	30	213	3	28.630	62	43	105	21	10	2	5
	7	31	160	9	29.045	93	38	130	18	5	4	7
Model	8	31	88	7	28.967	74	37	111	11	2	4	7
Calibration	9	30	158	7	28.937	52	26	77	15	6	4	7
	10	31	170	14	29.304	48	20	68	14	11	4	9
1994	11	30	59	12	29.261	37	15	51	7	3	3	9
	12	31	56	11	29.160	32	10	42	7	1	3	8
	Total	214	903	62	29.045	397	188	585	94	39	24	51
Model	1	31	43	11	29.170	30	8	39	5	2	3	8
Verification	2	28	44	9	29.126	32	10	42	5	1	2	7
	3	31	116	10	29.116	47	17	63	9	4	2	8
1995	4	30	93	11	29.239	53	21	74	9	6	3	8
	5	31	90	10	29.105	55	34	89	8	3	3	8
	Total	151	386	49	29.151	218	90	308	35	16	11	39

Note: E = Evaporation from the soil/water surface; T = transpiration from plants;
UDrain = water drained from the unsaturated zone to the saturated zone; Ds = vertical seepage through the underlaying clay layer.

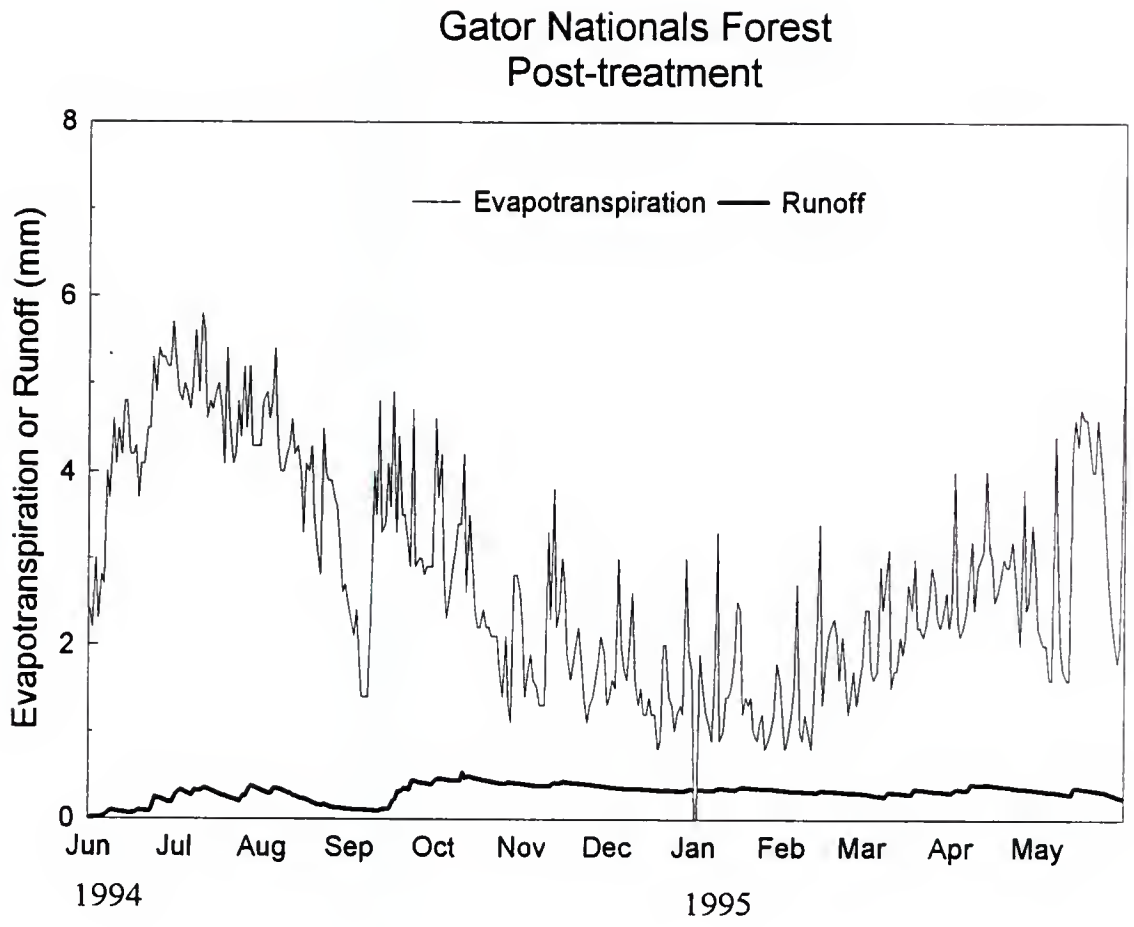


Figure 5.9. Simulated daily runoff and evapotranspiration from the Gator Nationals Forest site during model calibration and verification periods under post-treatment conditions.

Table 5.6. Summary of parameter values for the Gator Nationals Forest site calibrated by the FLATWOODS model from pre-treatment and post-treatment data.

Parameter	Value
Cell size	50 meter by 50 meter
LAI (all sided leaf area index)	Cypress wetlands: LAI(t) = 1.2 $t < 60$ LAI(t) = 1.2 + (3.93-1.2) / (121 - 61) t $60 < t < 121$ $LAI(t) = 1.5 + 4.4 \times Sin(\frac{1.1\pi}{365}t + 1.9\pi)$ otherwise t-Julian day Pine upland plantations: $LAI(t) = 2.25 + 0.25 \times Sin(\frac{2\pi}{365}t + 1.1\pi)$ Harvested wetlands: 0.5 Harvested uplands: 0.1

Root density (m/m^2)		layer 1	layer 2	layer 3
	Pre-treatment period	1588	243	850
	Post-treatment period	50	0	0

Soil parameters	K_s (cm/day)	θ_s	θ_r	n	f_c
	Wetlands				
	Layer 1	429.8	0.40	0.08	2.96	0.20
	Layer 2	261.6	0.35	0.08	2.96	0.20
	Layer 3	261.6	0.30	0.08	2.96	0.15
	Uplands				
	Layer 1	329.8	0.35	0.05	4.32	0.15
	Layer 2	200.6	0.35	0.06	2.34	0.18
	Layer 3	152.0	0.30	0.06	3.90	0.15

Table 5.6. (Continued)

Parameter		Value			
		layer 1	layer 2	layer 3	layer 4
Specific yield (S_y)	Cypress wetlands	0.14	0.05	0.073	0.03
	Pine uplands	0.14	0.05	0.070	0.03
	Harvested wetlands	0.20	0.05	0.073	0.03
	Harvested uplands	0.14	0.05	0.070	0.03
Runoff	K1	0.232			
	K2	1.309			
	K3	28.90			
	CSD (m):				
	Pretreatment	0.3			
	Post-treatment	0.4			
Deep seepage	Lc	0.007			
ET	Pre-treatment	PEC	1.30		
		CE1	0.50		
		CE2	1.40		
		CT1	1.00		
		CT2	20.0		
		CET	0.85		
	Post-treatment	PEC	1.30		
		CE1	0.50		
		CE2	1.00		
		CT1	0.80		
		CT2	20.0		
		CET	0.85		

by the recorded groundwater table levels in five shallow wells (Figure 5.11). Excluding the exceptionally dry year of 1981, an average Pearson Correlation Coefficient of 0.84 was obtained. Annual calibration results have been summarized in Table 5.7 The model was further verified with runoff data from 1983 to 1992 following the 5-year calibration period. These verification results are presented in Figure 5.13 and also summarized in Table 5.7. For

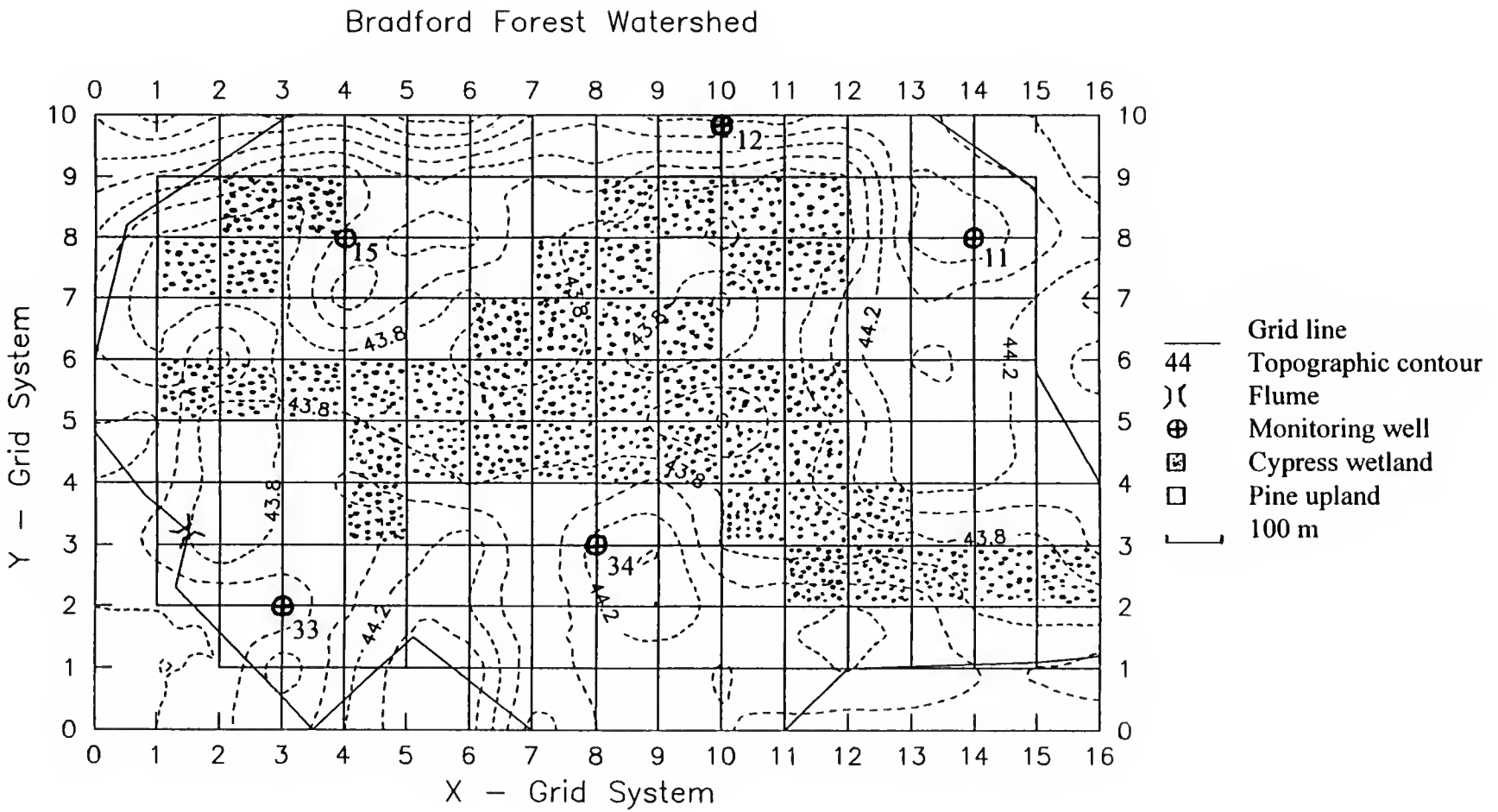


Figure 5.10. Physical information of the modeling units of the Bradford Forest site.

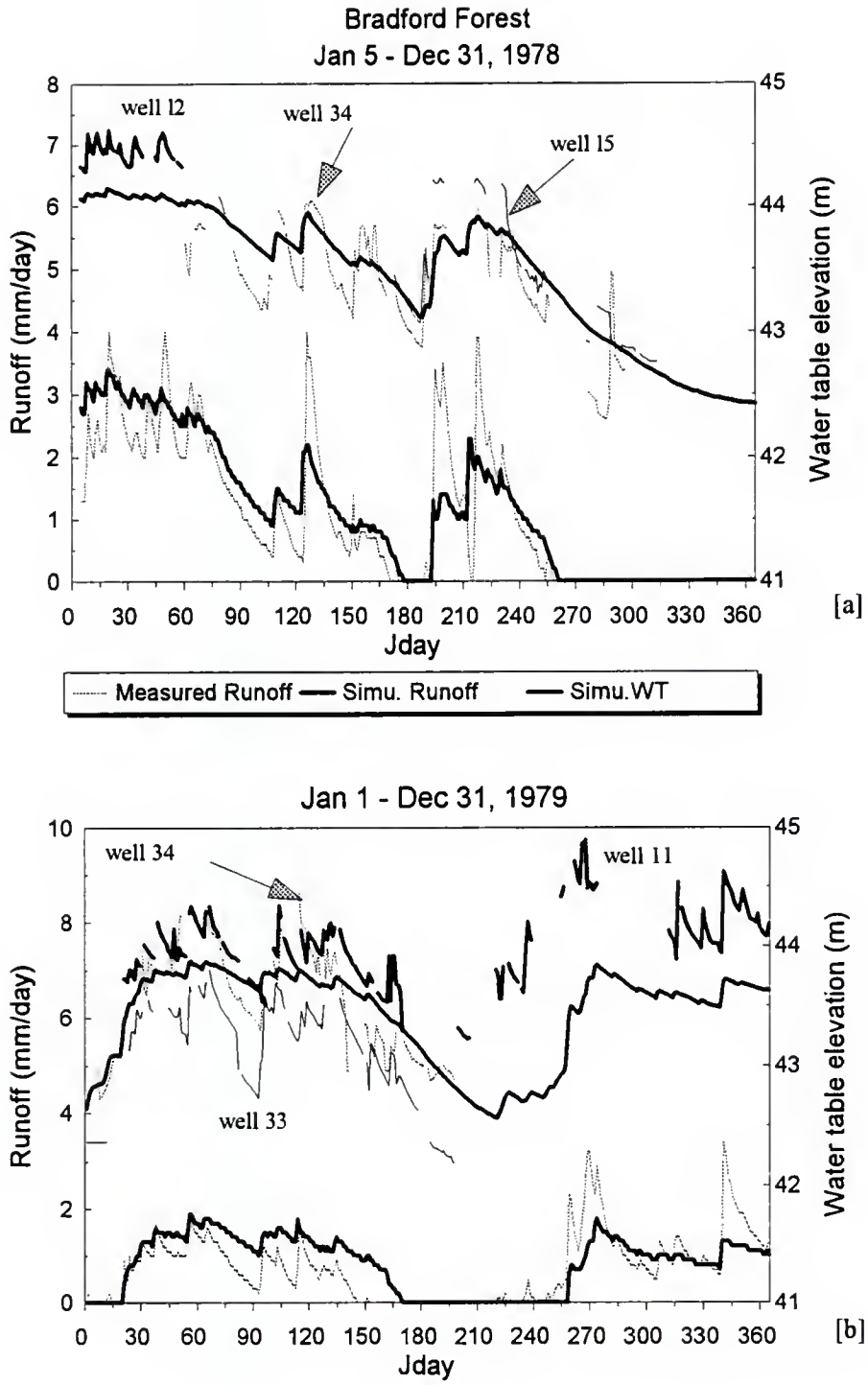


Figure 5.11. The FLATWOODS model calibration with measured runoff and groundwater table data in 1978 (a) and 1979 (b) from the Bradford Forest Watershed (WS3). The groundwater table data from the shallow wells were incomplete and were used as guides for the groundwater table fitting.

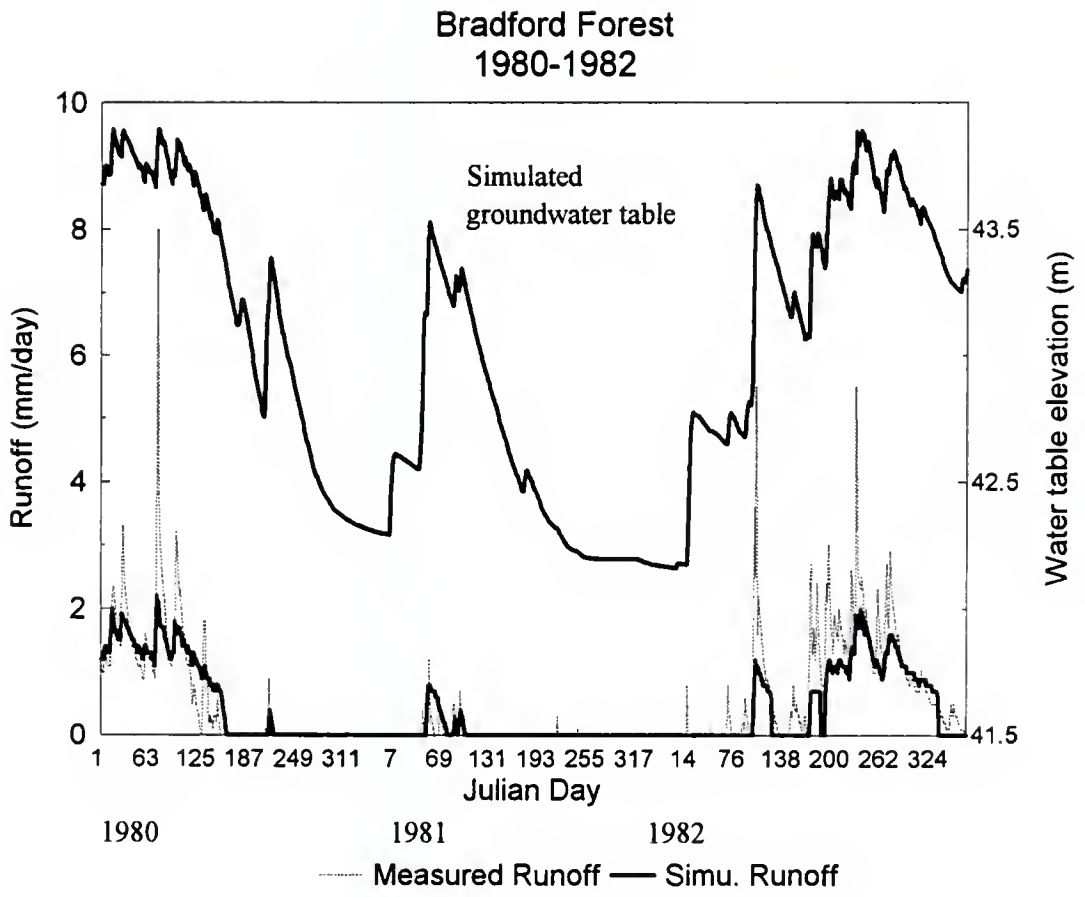


Figure 5.12. The FLATWOODS model calibration with measured runoff from the Bradford Forest Watershed during 1980-1982.

Table 5.7. Model calibration and verification results for the Bradford Forest Watershed.

	Year	Rainfall (mm)	Mea.Runoff (mm)	Simu Runof (mm)	Avg. Head (mm)	E (mm)	T (mm)	E+T (mm)	Inter. (mm)	UDrain (mm)	Ds (mm)	PCC
Calibration	1978	1453	380	412	43.457	163	721	884	205	861	54	0.88
	1979	1339	268	334	43.458	139	759	897	247	607	38	0.75
	1980	1137	217	210	43.141	118	785	903	200	424	97	0.86
	1981	916	12	16	42.562	19	745	764	158	164	41	0.64
	1982	1449	299	252	43.418	125	855	979	251	669	41	0.86
Verificatio	1983	1628	462	310	43.519	144	774	918	252	82	129	0.61
	1984	1204	236	216	43.249	117	822	939	194	46	89	0.86
	1985	1281	234	132	42.936	50	818	869	240	40	61	0.89
	1986	1292	261	156	43.267	90	846	936	245	42	76	0.72
	1987	1257	234	194	43.262	92	766	859	184	53	87	0.85
	1988	1460	301	271	43.371	104	702	806	221	70	110	0.79
	1989	942	17	0	42.598	3	823	826	197	10	8	-0.14
	1990	780	12	0	42.061	3	747	750	146	5	4	0.19
	1991	1591	293	218	43.271	138	775	913	244	77	101	0.81
	1992	1518	431	296	43.498	136	783	918	245	74	119	0.62

Note: E = simulated evaporation;
T = simulated transpiration;
Inter = simulated canopy interception;
UDrain = water drained from the unsaturated zone to the water tabel aquifer;
Ds = vertical seepage through the underlaying clay layer;
PCC = Pearson Correlation Coefficient.

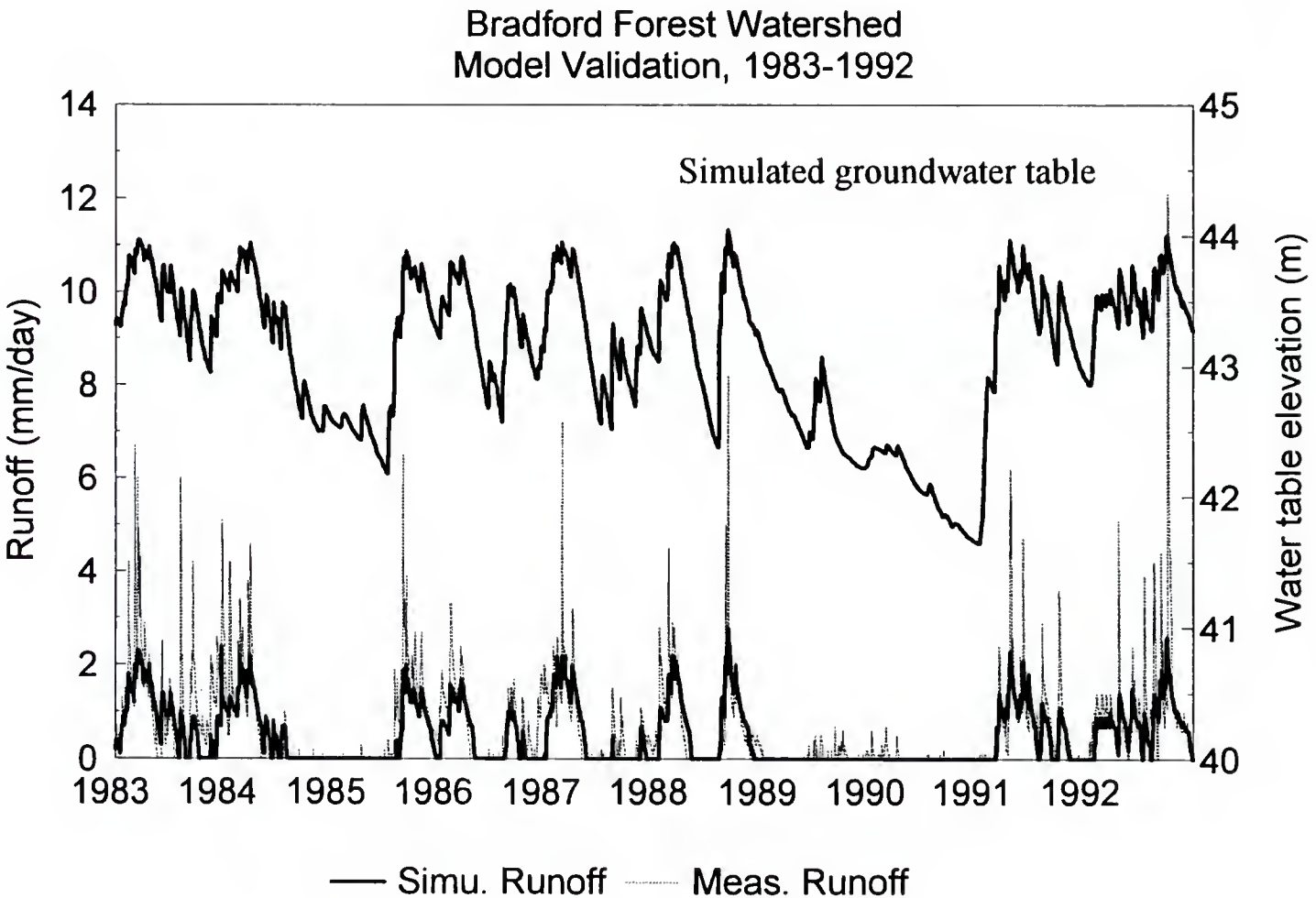


Figure 5.13. The FLATWOODS model verification with measured runoff data (1983 - 1992) from the Bradford Forest Watershed.

ten years of simulation, the model showed encouraging predictability and stability as demonstrated by the high Pearson Correlation Coefficients for most of the years. However, the model could not predict the extremely high flows very accurately causing underprediction of runoff in wet years (1983 and 1992). Two reasons have been hypothesized: (1) the boundary and outlet ditches in this artificially created watershed may generate higher peak flows during the wet seasons, especially in extreme years (Iritz et al., 1994); and (2) the FLATWOODS model used a single runoff-water table level relationship independent of time o predict runoff, and no cell-by-cell surface flow routing procedures had been introduced. The assumption made in the runoff-groundwater table relationship seemed very effective since the model could also fit the low flow reasonably well during the two-year drought period of 1989 -1990. Final calibrated model parameters for the watershed at the Bradford Forest have been listed in Table 5.8. Compared with the GNF site, the calibration revealed that the Bradford Forest site had lower K_s and soil thickness values, but a higher CSD (Critical Soil Depth) value.

Model Sensitivity Analysis and Application

Model Sensitivity Analysis and Application Schemes

The model sensitivity analysis procedure involves evaluation of model responses to parameter perturbations. To get accurate simulation results, sensitive parameters must be measured or cited from the literature more carefully. In practical model applications, the sensitivity analysis is also useful to project the consequences of certain model input changes,

Table 5.8. Summary of parameter values for the Bradford Forest Watershed calibrated by the FLATWOODS model with data from 1978-1982.

Parameter	Value					
Cell size	100 meter by 100 meter					
LAI (all sided leaf area index)	Cypress wetlands: $LAI(t) = 1.2$ $t < 60$ $LAI(t) = 1.2 + (3.93 - 1.2) / (121 - 61)\, t$ $60 < t < 121$ $LAI(t) = 1.5 + 4.4 \times Sin(\frac{1.1\pi}{365} t + 1.9\pi)$ otherwise t-Julian day Pine upland plantations: $LAI(t) = 5.0 + 0.9 \times Sin(\frac{1.8\pi}{365} t + 0.9\pi)$					
Root density (m/m^2)		layer 1	layer 2	layer 3		
		1588	243	850		
Soil parameters	K_s (cm/day)		θ_s	θ_r	n	f_c
	Wetlands					
	Layer 1	150.0	0.40	0.08	2.96	0.20
	Layer 2	150.0	0.35	0.08	2.96	0.20
	Layer 3	100.0	0.30	0.08	2.96	0.15
	Uplands					
	Layer 1	150.0	0.35	0.05	4.32	0.15
	Layer 2	150.0	0.32	0.06	2.34	0.18
	Layer 3	100.0	0.30	0.06	3.90	0.15

Table 5.8. (Continued)

Parameter		Value
Runoff	K1	0.632
	K2	2.309
	K3 (m)	43.28
	CSD (m)	0.40
Deep seepage	Lc	0.138
Evapotranspiration	PEC	1.30
	CE1	0.40
	CE2	1.40
	CT1	0.00
	CT2	20.0
	CET	0.80

such as species conversion, land development, drainage etc.. Although the sensitivity analysis is often performed after the model calibration and verification procedures with a standard data set, this process is actually implied in the model calibration. Adjusting the more sensitive parameters will result in more variation in the model output and insensitive parameters are less important to the model performance. From the model calibration experience, the author concluded that the FLATWOODS model is most sensitive to the following parameters: (1) correction factor for potential evapotranspiration (PEC) calculated by Hamon's method; (2) soil porosity, specific yield (S_y) and the thickness of the surficial aquifer; and (3) parameters (K1, K2, K3, CSD) used in describing the runoff-groundwater table relationship. In this simulation study, sensitivity analysis procedures were incorporated into 13 simulation scenarios using different model input combinations to study the hydrologic effects of common forest management practices in pine flatwoods (Table 5.9).

Table 5.9. Simulation schemes to study the potential harvesting effects in the first year and long-term on pine flatwoods hydrology at the Gator Nationals Forest and Bradford Forest sites.

Site	Climatic condition	Harvesting Methods			
		Control	Treatment 1 (Cypress wetlands only)	Treatment 2 (Pine uplands only)	Treatment 3 (Wetlands and uplands)
Gator Nationals Forest (GNF)	Normal year (1986)	Case 1	Case 2	Case 3	Case 4
	Dry year (1977)	Case 5	Case 6	Case 7	Case 8
	Wet year (1964)	Case 9	Case 10	Case 11	Case 12
Bradford Forest (BF)	Long term (1978-1992)				Case 13

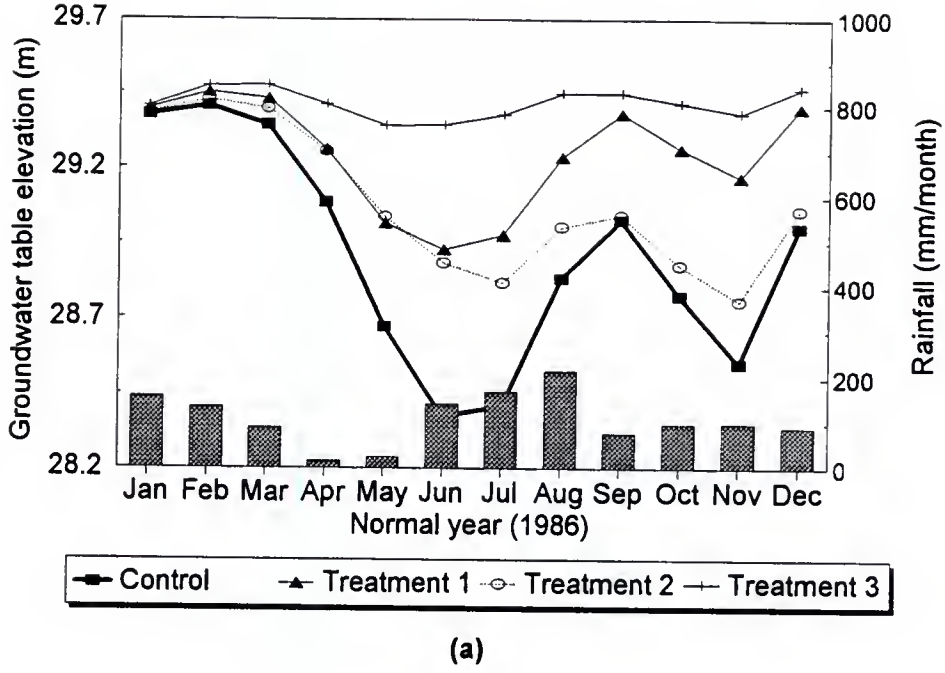
Three different climatic conditions in 1964, 1977, and 1986 were selected from a 60-year historical weather record from the University of Florida, IFAS, Agronomy weather station, representing a wet year, a dry year and a normal year at the Gator Nationals Forest (GNF) site. Treatment methods included a Control (no harvesting), Treatment 1 (harvesting cypress wetlands only), Treatment 2 (harvesting pine uplands only), and Treatment 3 (harvesting both wetlands and uplands). Cypress wetlands covered about 35% of the GNF study area with the remaining 65% in upland pine plantations. The simulation schemes were designed to predict the first year response to three different harvesting operations under three climatic conditions (Table 5.9). In addition, a long term simulation was performed to study the hydrologic responses during the development of a young pine flatwoods for a full 15-year

stand rotation at the Bradford Forest site. The final calibrated model parameters (Tables 5.6 and 5.8) were used in all the following case studies. A representative spatial distribution of the groundwater table was employed to initialize the simulation model.

Simulation Results

Gator Nationals Forest site - first year responses

Normal year. The year of 1986 had a typical rainfall pattern for Alachua County, showing high rainfall in the winter and summer but a drought period in the spring and the late fall (Figure 5.14). The simulation results demonstrated that the groundwater tables had a significant rise for all three treatments during the summer and fall months. Clear-cutting both cypress ponds and pine uplands resulted in the most pronounced effects on groundwater tables as well as runoff. Harvesting pine uplands only (Treatment 2) caused a maximum water table increase of 51.7 cm in June, but no significant increase of runoff for most of the time in 1986. The higher increase in water levels and runoff by Treatment 1 (harvesting wetlands only) than by Treatment 2 suggested that flatwoods hydrology was more sensitive to wetlands disturbance than uplands in this landscape. Harvesting of the wetlands may have increased the extent of saturated depression areas and thus caused more runoff than harvesting uplands only. The uplands had less water storage capacity, but under normal weather conditions this factor did not dominate the harvesting effects on the hydrology. Removal of both pine and cypress forests reduced plant transpiration and canopy interception substantially, but, in exchange, soil evaporation increased significantly. The net result was less water loss from the treated land. Evaporation from the sandy soils was usually limited



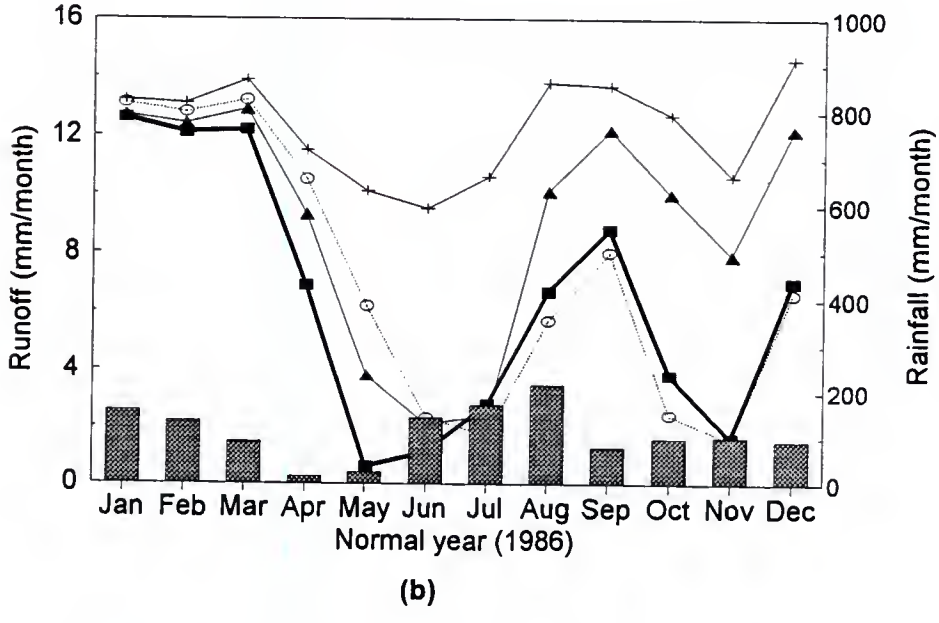
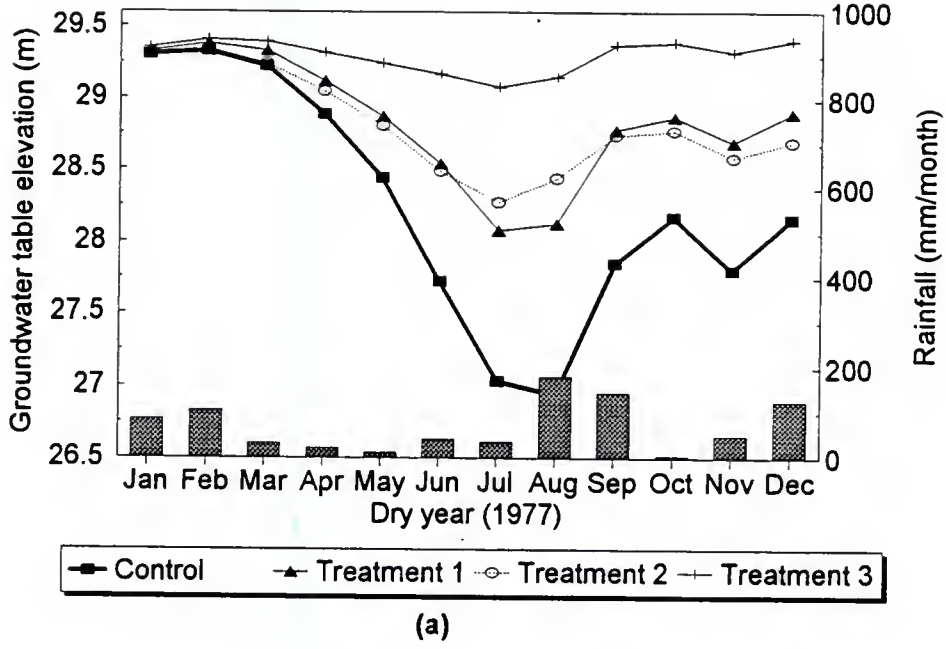


Figure 5.14. Simulated dynamics of the groundwater tables (a) and runoff (b) in a normal year showing different treatment effects of three harvesting methods.

as the water table was below the 35-cm depth (Hillel, 1980; Phillips, 1987).

Dry year. The year 1977 was an extremely dry year with a 493-mm rainfall deficit that mostly occurred during the first half of the year (Figure 5.15). As in the normal year, water tables were significantly raised by all treatments. However, Treatment 1 and Treatment 2 showed very similar effects on the groundwater table rise and the runoff increase patterns. Harvesting both wetlands and uplands increased runoff tremendously from the early spring season to the end of the year, but during this period no significant runoff was found from the other two treatment conditions. Negative values of runoff suggested net inflow from outside the system boundaries.

Wet year. The selected extremely wet year of 1964 had a surplus of 666-mm rainfall compared to the normal year of 1986. Due to the higher rainfall input in April and thus more water stored, the groundwater tables did not decline so rapidly as in the normal year or the dry year (Figure 5.16). Although the wet year also experienced a dry period in May and June, significantly more rainfall input in the subsequent months from July to September eventually flooded the entire watershed with the water table approaching the ground surface (29.43 m in elevation). In the extremely wet season, forest harvesting did not affect the hydrology as significantly as in the relatively dry season (April-June). As in the previous two cases, removal of vegetation in both wetlands and uplands resulted in the highest perturbation of runoff and the groundwater table rise. Less influence was induced by the two partial harvesting methods than the whole vegetation removal method. Treatment 1 and Treatment 2 showed no significant difference in their effects on groundwater table and runoff. Under high water table conditions, the water loss from the system was dependent on



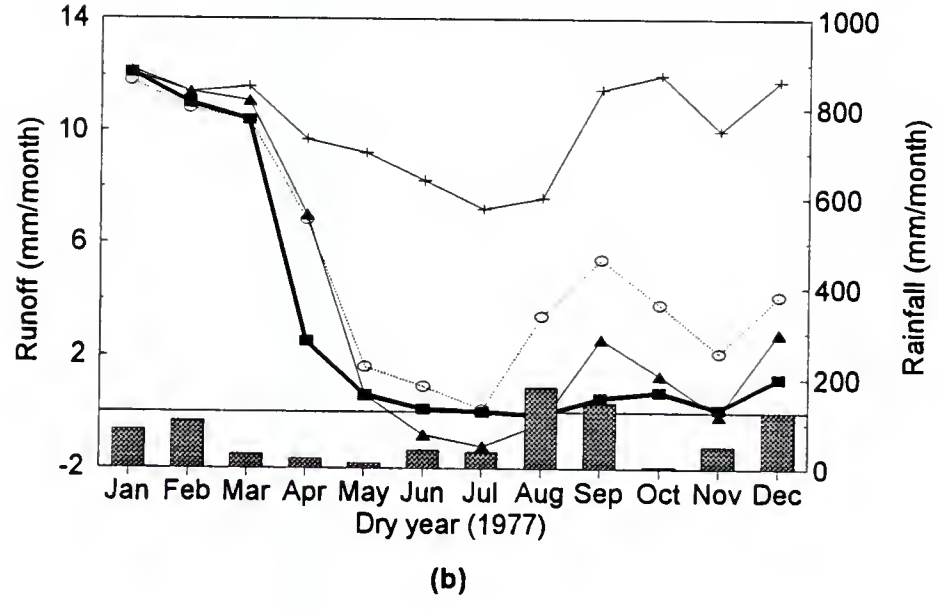


Figure 5.15. Simulated dynamics of the groundwater tables (a) and runoff (b) in a dry year showing different treatment effects of three harvesting methods.

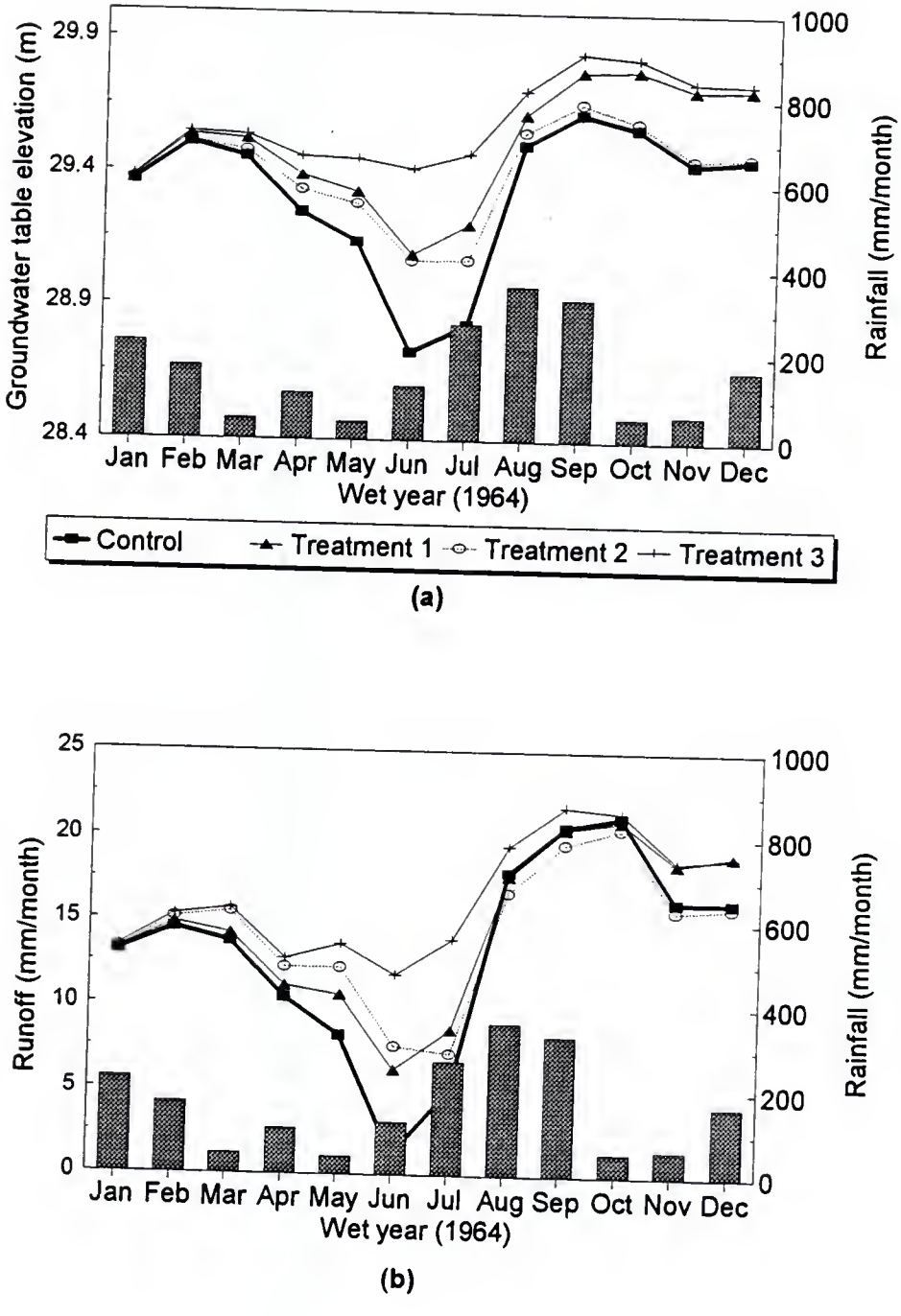


Figure 5.16. Simulated dynamics of the groundwater tables (a) and runoff (b) in a wet year showing different treatment effects of three harvesting methods.

available solar energy or potential evapotranspiration rather than transpiration by plants. When the groundwater table was close to the ground surface or above the surface (e.g. ponds), the water table responded less due to higher soil porosity and specific yield. Rapid surface runoff or near-surface subsurface runoff was considered a factor causing a lower increase in the groundwater table by storms during the wet seasons.

Comparison of harvesting methods under different climatic conditions. Simulated annual hydrologic components have been summarized in Figure 5.17 and Table 5.10 to show the different effects of the three treatment methods under various climatic conditions. Statistical analysis of ANOVA using Tukey's Test (SAS, 1985) was performed to group the treatment methods by their effects on the variables of runoff, groundwater table, and evapotranspiration using the simulation results of the three different years. In general, no significant difference ($\alpha = 0.001$) was found among the Control, Treatment 1 and Treatment 2 groups in affecting the three variables. However, clear-cutting both wetlands and uplands however showed significant effects on the runoff and groundwater tables. Examining Table 5.10 in detail, one may conclude that the harvesting effects become more pronounced in a dry year than in a wet year. During a dry year, Treatment 1 and Treatment 2 apparently also caused significant hydrologic impacts, increasing runoff by 18-56% and the groundwater table level by about 60 cm.

Bradford Forest Watershed - long term study

This simulation was designed to show the long term hydrologic responses following forest stand development after clear-cutting the mature forests at the Bradford Forest in 1978. Since the FLATWOODS model had been calibrated and verified with measured data under

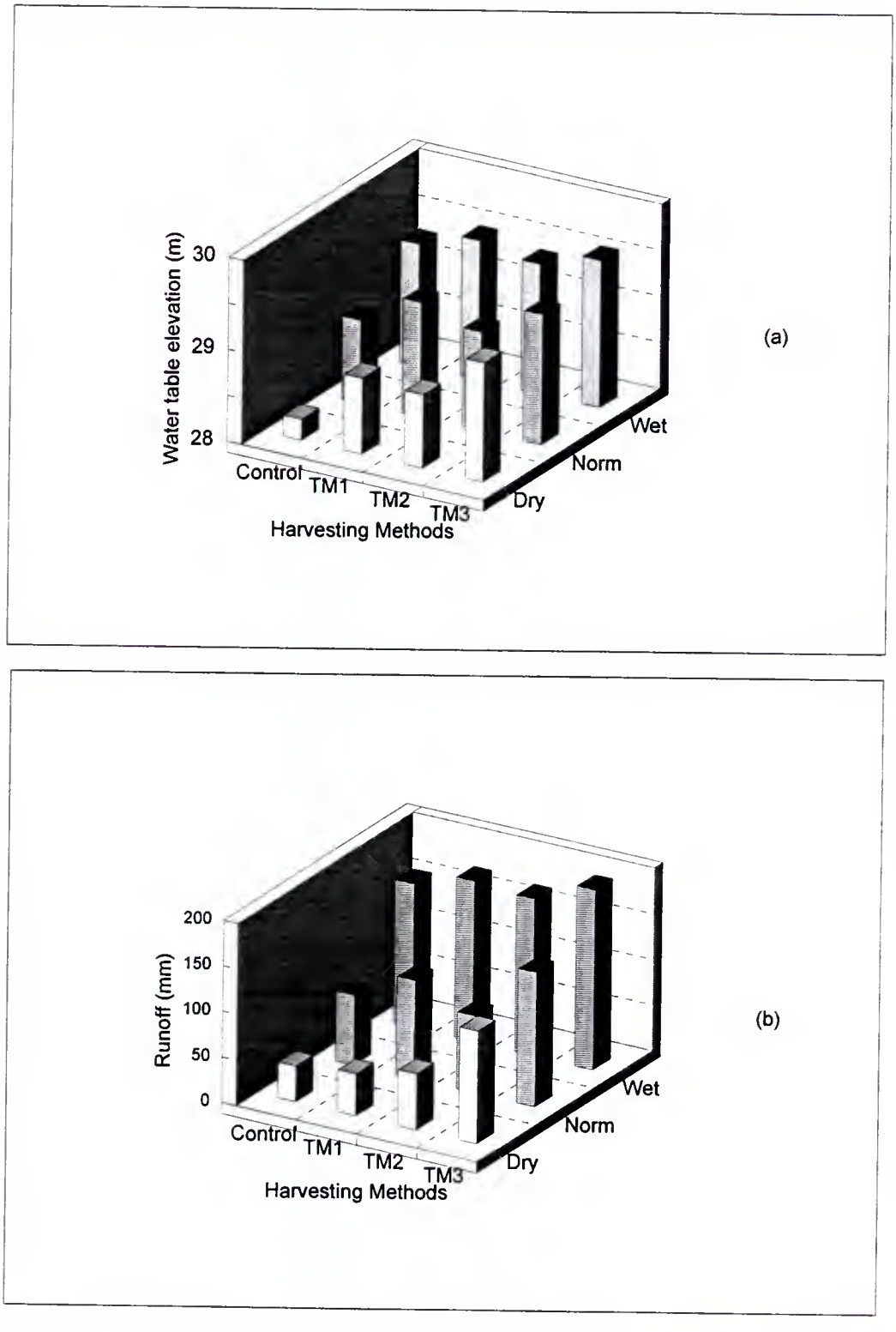


Figure 5.17. Comparison of treatment effects on annual average groundwater table elevations (a), annual total runoff (b), and annual total evapotranspiration (c) under three climatic conditions. TM1 = treatment 1, wetlands harvesting only; TM2 = treatment 2 = uplands harvesting only, TM3 = treatment 3 = wetlands and uplands harvesting.

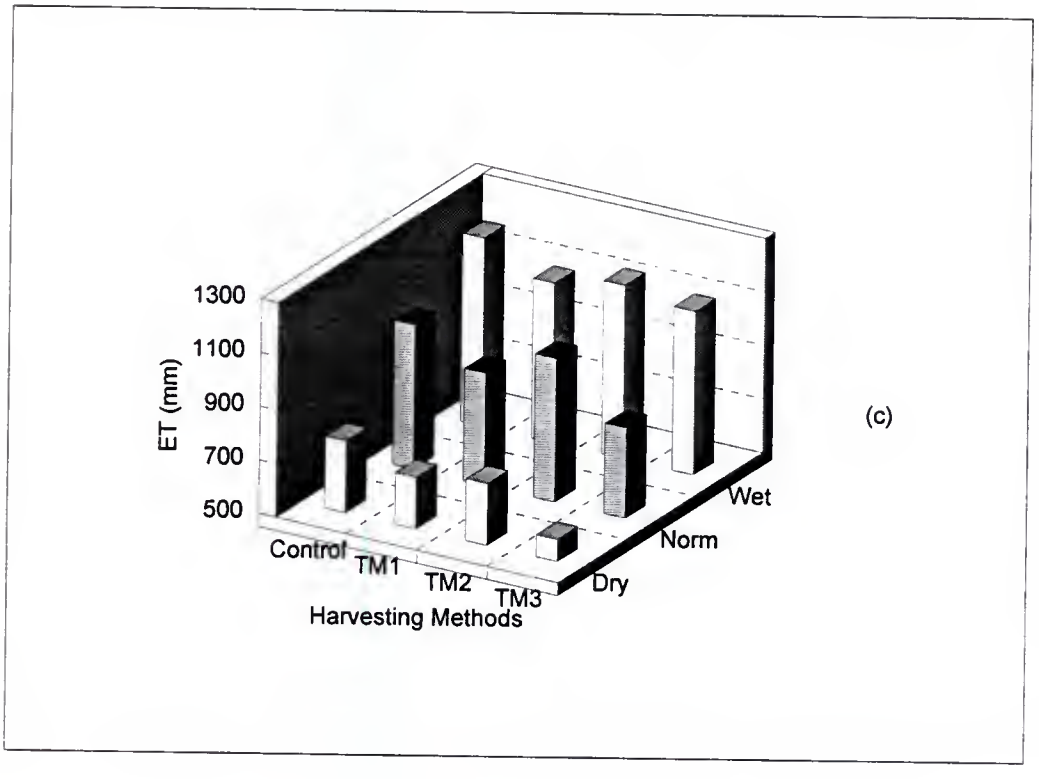


Figure 5.17. (--- continued) Comparison of treatment effects on annual average groundwater table elevations (a), annual total runoff (b), and annual total evapotranspiration (c) under three climatic conditions. TM1 = treatment 1, wetlands harvesting only; TM2 = treatment 2 = uplands harvesting only, TM3 = treatment 3 = wetlands and uplands harvesting.

Table 5.10. Simulated hydrologic effects of forest harvesting under three climatic conditions in pine flatwoods.

Climatic conditions		Dry year	Norm year	Wet year
	Precipitation (mm)	836	1329	1955
Runoff (mm)	Control	39	76	158
Runoff increase†	Treatment 1	0.18	0.42	0.11
	Treatment 2	0.56	0.11	0.09
	Treatment 3	2.15	0.93	0.25
Avg. groundwater table elevation (m)	Control	28.227	28.899	29.322
Groundwater table rise (cm)	Treatment 1	60	34.3	18.7
	Treatment 2	57.4	17.5	8.2
	Treatment 3	107	51.5	27.4
Evapotranspiration (mm)	Control	769	1037	1202
Evapotranspiration reduction‡	Treatment 1	0.1	0.11	0.09
	Treatment 2	0.05	0.00	0.05
	Treatment 3	0.24	0.19	0.08

†Runoff increase = (runoff by treatment - runoff by control)/runoff by control
‡Evapotranspiration (ET) reduction = (ET by control - ET by treatment)/ET by control

forested conditions, it was advantageous to use the same data during 1978-1992 to study the hydrologic effects due to harvesting. The leaf area index (LAI), as the only biomass accumulation indicator, was assumed to reach 60% and 100% of the maximum for a mature stand at the age of five and fifteen years, respectively. The following equation, fitted from a pine biomass study (Gholz and Fisher, 1982), was used to describe the dynamics of the LAI

correction factor (CLAI) as a function of time (year):

$$CLAI(t) = 0.2 \qquad t < 2$$

$$CLAI(t) = 1.0 \qquad t > 15$$

$$CLAI(t) = (t - 1.5)/(t + 0.01) \qquad \text{otherwise}$$

Where, t = the number of years after forest harvesting.

Simulated groundwater table elevations under untreated and treated conditions are depicted in Figure 5.18 and Figure 5.19. These two graphs show that forest clear-cutting significantly raised groundwater table levels by 20-80 cm on an annual average. The most drastic increase occurred during dry years in 1981, 1984, 1989 and 1990 when the groundwater tables were down in the deepest soil layers, which had lower specific yield and porosity. Measured runoff under the control condition (no harvesting), simulated runoff under the treatment condition (assuming the harvest is completed by January 1, 1978), and simulated evapotranspiration under the control and treatment conditions have been presented in Figures 5.20 and 5.21. Runoff substantially increased during the first six years 1978-1984 by an average of 200 mm after the treatment was imposed in 1978. The dry year of 1981 showed a maximum runoff increase of 12 folds during the 15-year simulation. However, since there was little runoff the harvesting effects had little impact downstream. Unlike the dry year of 1981, the two continuous dry years of 1989 and 1990 had no significant runoff increase due to the increased transpiration by recovered vegetation. The groundwater tables in 1989 and 1990 were elevated significantly but not high enough to cause the runoff to increase. The significant reduction of evapotranspiration loss of 100-300 mm after the forest removal apparently contributed to the runoff increase and the groundwater table elevation.

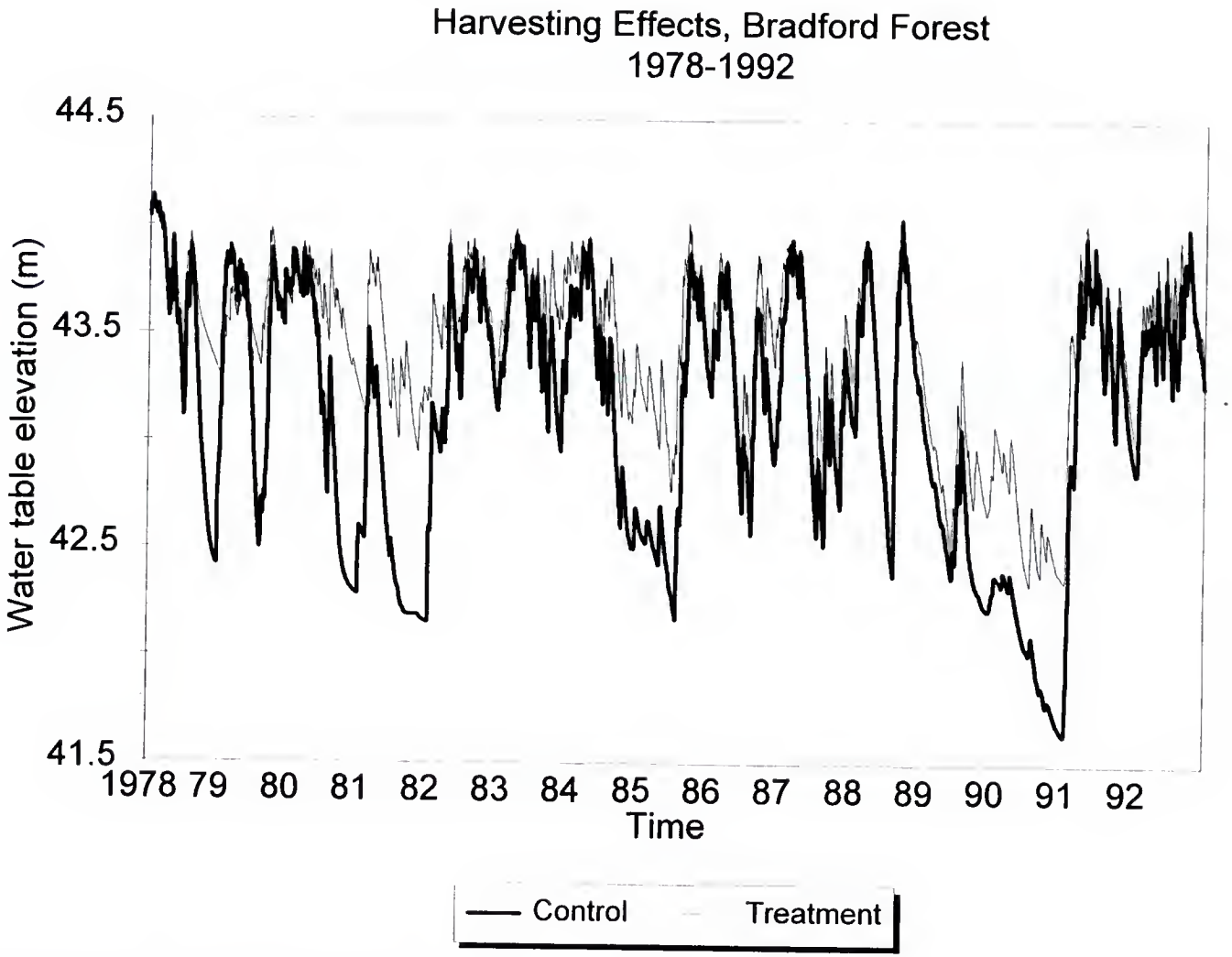


Figure 5.18. Simulated long-term effects of forests clear-cutting on groundwater table dynamics during a 15-year stand rotation. The treatment is assumed to be completed by January 1, 1978.

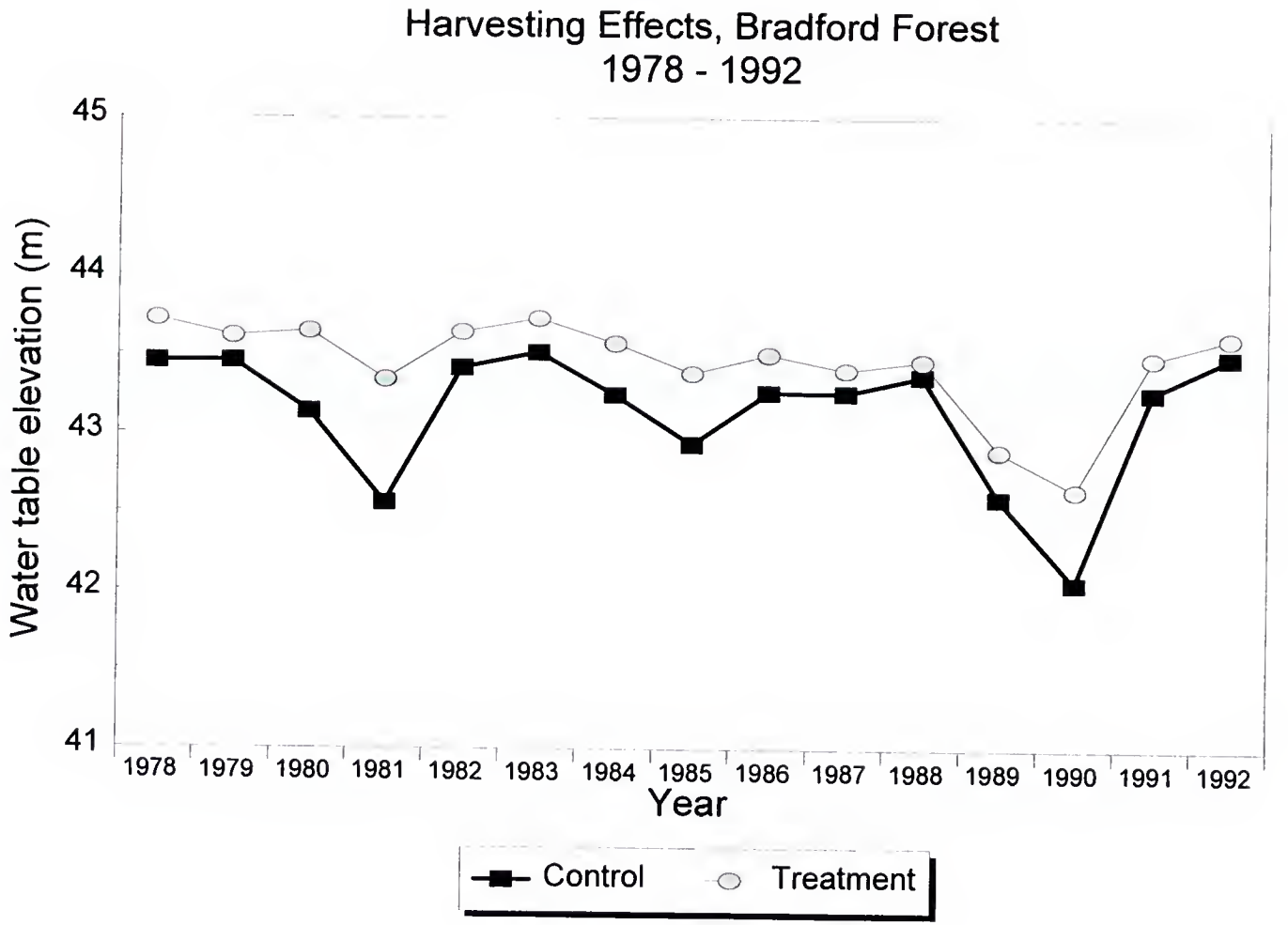


Figure 5.19. Simulated long-term effects of clear-cutting on the annual average groundwater table level during a 15-year stand rotation. The treatment is assumed to be completed by January 1, 1978.

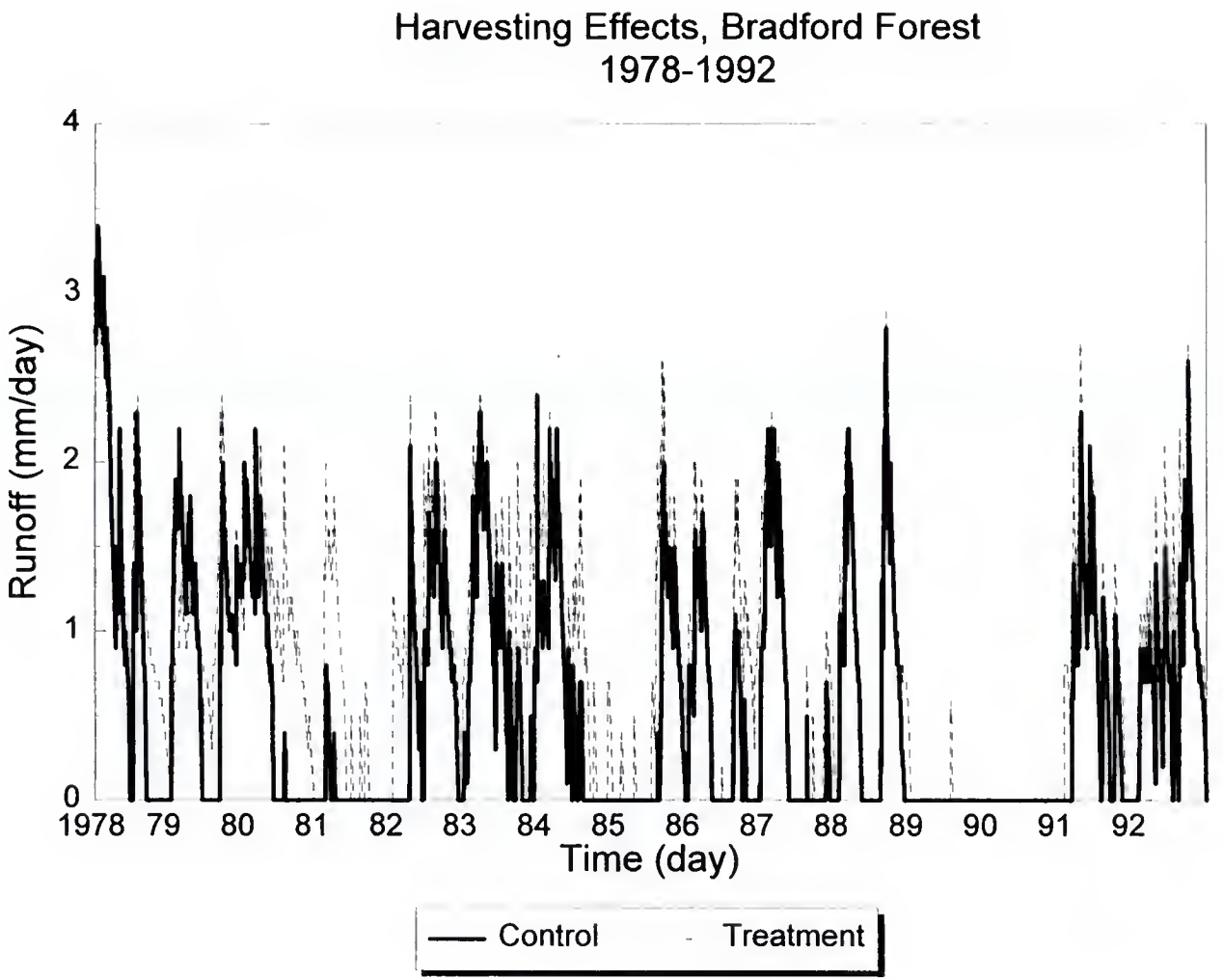


Figure 5.20. Simulated long-term effects of clear-cutting on daily runoff during a 15-year stand rotation. The treatment is assumed to be completed by January 1, 1978.

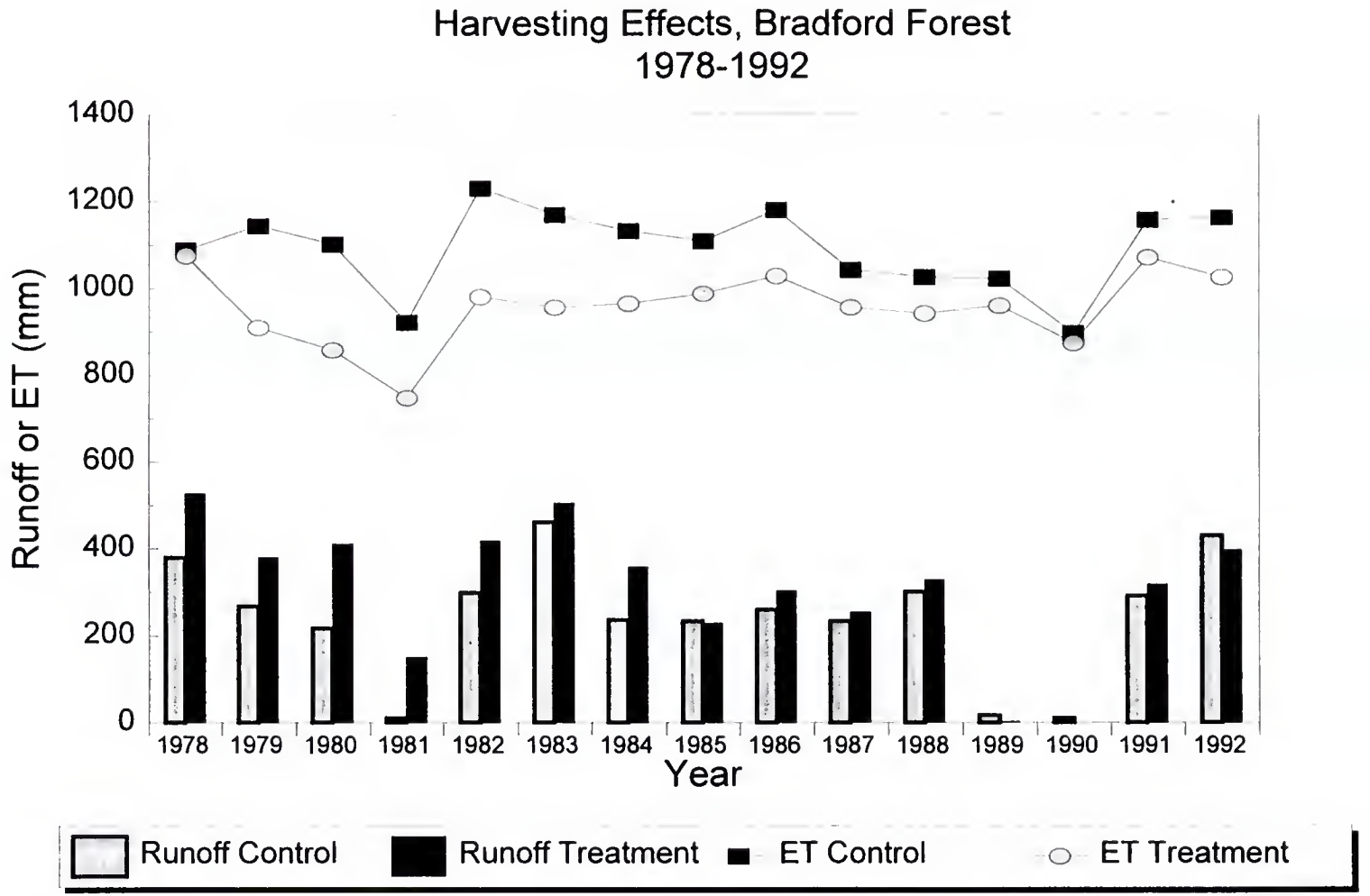


Figure 5.21. Simulated long-term effects of clear-cutting on annual runoff and evapotranspiration during a 15-year stand rotation. The treatment is assumed to be completed by January 1, 1978.

A comprehensive survey of effects of vegetation changes on water yield and evapotranspiration for 94 catchment experiments around the world was reported by Bosch and Hewlett (1982). They concluded that reductions in pine forest cover increased water yield about 40 mm per 10% change in cover. They also found that the water yield changes after clear-cutting were positively related to the precipitation of the specific year of treatment. The increase of water yield after clear-cutting varied from 100 mm to 600 mm in the zone with annual precipitation of 1200 - 1400 mm, which is the approximate amount of rainfall for this study. According to this simulation study, it appears that clear-cutting of pine forests on flatwoods causes an increase of runoff in the low range as compared to that in other regions. However, due to the flat topography of pine flatwoods ecosystems, the changes in water storage and groundwater table are expected to be more pronounced than those of other systems.

This case study suggested that pine flatwoods are storage-based hydrologic systems where the groundwater table dictates the surface runoff; the groundwater level is controlled by both the precipitation input and the evapotranspiration output. Clear-cut harvesting significantly reduced water loss by evapotranspiration, significantly elevating runoff from pine flatwoods. Runoff increases became insignificant around the 10^{th} year after the treatment while the groundwater table effects were somewhat prolonged. Riekerk (1989) studied the hydrologic influence of two silvicultural practices (high site disturbance and low site disturbance) by a paired-watershed experimental method (regression method) at the Bradford Forest. He found that the increase of runoff from the high-disturbance watershed dropped from 150% in the first year to 60% of the predicted in the 6^{th} year of post treatment,

implying the hydrology of this watershed would return to pre-harvesting conditions in the 11^{th} year, but the water table returned to normal about eight years after treatment (Riekerk, personal communication). The present simulation study corroborated these conclusions, showing the strength and promise of the FLATWOODS model for forest water management.

CHAPTER 6
SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

This dissertation documented a four-year comprehensive study of the pine flatwoods hydrology with significant attention given to the interactions between the surface water and the shallow groundwater in the wetland/upland systems. The water balance equation was used as a guide for field data collection at two different study sites. Hydrologic processes in the pine flatwoods were studied in detail at the Gator Nationals Forest site by monitoring spatial and temporal dynamics of the canopy interception, groundwater table, soil moisture content, groundwater flows and surface flows.

Soil moisture content showed a close relationship with the groundwater table level except in the 0-20 cm soil layer in uplands. A formula was developed to describe these relationships and used to initialize the new FLATWOODS model. The soil moisture content decreased from wetlands to the surrounding uplands. Soils under the cypress forest canopies had significantly higher soil moisture content than upland soils, even during the drought year of 1993.

Groundwater tables in the pine flatwoods, characteristic of flat topography with porous yet poorly drained soils and high evapotranspiration, showed very dynamic and distinct patterns compared with other groundwater systems. The temporal distribution of the

groundwater table depth was controlled by rainfall patterns and evapotranspiration in various time scales from hours to years. Groundwater tables generally were the highest in the winter months and the lowest in the spring dry season. These typical patterns were altered if more rainfall occurred during the spring months. Generally, the groundwater tables followed the topographic surface during high water table conditions, but reversal gradients also developed at the wetland-upland margins during the early spring transition season in April.

Groundwater movement in pine flatwoods was low, even though the saturated hydraulic conductivity of flatwoods soils was high. The reason was attributed to low hydraulic gradients. As a result, groundwater flow was not a major component in the hydrologic budgets of wetlands or uplands. The groundwater flow might be more important during storms with high water table regimes with respect to pollution concerns by upland activities.

Surface flows were not common in the pine uplands. Surface flows were mostly generated in cypress wetlands and associated inter-wetlands low areas, including ditches. Runoff from wetlands mostly occurred during the winter months from January to March, which corresponded to the high water table conditions and dormant season of cypress trees in these systems. The surface area of saturated cypress wetlands expanded gradually with the net increase of water storage in the fall season. Due to the low topographic gradients at the pond margins, the expansion of the wetlands area (variable source area) was found to be extremely rapid during winter storms when the water levels were already high. The mechanisms of rainfall-on-water (Dunne type overland flow theory) might explain most of the stormflow generation from wetlands.

Over 85% of the annual rainfall in a flatwoods system was returned to the atmosphere by evapotranspiration, of which 12-14% was canopy interception. Evaporation loss from the soil/water surface was substantially reduced by microclimatic effects of the closed cypress forest canopies, but the total water loss through evapotranspiration from wetlands was not significantly lower than pine uplands due to the higher leaf area index in these wetlands.

Based on the existing COASTAL model, a new distributed forest hydrologic model, FLATWOODS, was developed. The FLATWOODS model was specifically designed to simulate the hydrologic processes in forested wetland-upland systems, where saturated and unsaturated soil zones coexisted and the surface water and subsurface water interacted. Vertically, the model divided a flatwoods hydrologic system into three connnected subsystems, an atmosphere/vegetation subsystem, an unsaturated water flow subsystem, and a groundwater flow subsystem. Laterally, the model divided the entire watershed into small rectangular cells which served as the simulation units. The present model employed deterministic equations to calculate the water balances of each subsystem on a daily time step with readily available climatic data and measurable parameters. The FLATWOODS model has the capability to predict daily groundwater table levels, evapotranspiration, soil water storage in up to three layers, and total daily runoff from a watershed subject to various boundary conditions. Major modifications and improvements of the original COASTAL model for development of the FLATWOODS model included: 1) the Van Genuchten equation for unsaturated water flow subroutine; 2) an algorithm to account for the upward water flux was added in the soil water balance equation of the evapotranspiration subroutine; 3) an algorithm for surface runoff routing was developed to use the variable source area

concept for stormflow generation; 4) algorithms to describe the dynamics of the leaf area index on a daily and an annual basis were derived from published data; 5) the soil moisture content distribution was initialized internally by the model using the soil moisture content-groundwater table relationships; and 6) variable values of specific yield and hydraulic conductivity rather than fixed ones were introduced.

The FLATWOODS model was calibrated and verified with extensive field-scale (42 ha) groundwater table data at the Gator Nationals Forest site. The period of three and a half years covered a wet year and a dry year, and both pre-treatment and post-treatment experiments were involved. Verification results were acceptable and demonstrated the strength of FLATWOODS in groundwater table modeling. In lieu of runoff measurements at the GNF site, the model was further tested at the watershed-scale (140 ha) at another research site, the Bradford Forest, with a 15-year set of runoff data. Although the model did not match the extremely high flows, in general encouraging results were obtained by this long term simulation.

The FLATWOODS outputs were most sensitive to parameters which represented physical properties important to water table variations, such as soil porosity and specific yield. Leaf area index (LAI) was an important parameter and model input variable for the model, influencing rainfall distribution, evapotranspiration, groundwater table level and runoff. Uncertainty existed in the prediction of runoff due to empiricism involved in developing the runoff-water table relations. So, caution must be taken in the application of the model to other landscapes. In total, thirteen different scenarios were simulated by the model. The objectives were to test the model sensitivity to different model input

combinations, and to compare the hydrologic effects of three commonly used harvesting strategies. The simulation results matched experimental data reasonably well. Harvesting both wetlands and uplands showed the most significant effects on all model outputs. Partial harvesting activities of wetlands or uplands also showed significant effects on the groundwater table depth, but mostly during dry seasons. Higher rainfall caused higher water table levels and runoff, but the harvesting effects decreased proportional to the increase of the rainfall amount. The 15-year long term simulation of the young plantation showed that the runoff from the pine flatwoods at the Bradford Forest had the highest runoff and groundwater table increase during the first six years after treatments had been imposed. The water regimes tended to recover to the norm by about the 10^{th} year.

Conclusions

1. Pine flatwoods are heterogeneous hydrologic systems in which the surface water and the groundwater coexist and interact through the wetland-upland interfaces and the atmosphere-plant-soil systems.
2. Florida's pine flatwoods are storage-based hydrologic systems. Surface flow is dictated by the groundwater table level rather than the infiltration rate of the surface soil.
3. Stormflows from pine flatwoods are generated from the variable source areas represented by the enlarged wetland areas during the wet seasons. Dunne-type overland flows rather than Hortonian flows dominate the runoff mechanisms of pine flatwoods.
4. Tremendous variability of spatial and temporal distributions of groundwater table level and runoff exists in the pine flatwoods system. The spatial variability is determined

by the land topography and vegetation distribution; while the temporal variability is mainly dependent on the annual rainfall pattern and plant phenology.

5. Coupling a saturated water flow model with an unsaturated water flow model and an evapotranspiration model proves to be a suitable way to study the watershed scale pine flatwoods hydrology with adequate accuracy for management purposes.
6. The present simulation study suggests that silvicultural practices can cause significant impact on the hydrology in pine flatwoods, especially during the first 6 years after treatments. The disturbed hydrologic regime may return to the norm by the 10_{th} year. Partial harvesting methods show less effects than the total tree removal method. Clear-cutting of a mature pine flatwoods forest has a potential to reduce evapotranspiration by approximately 20%, increase runoff by up to 100% and elevate the water table level by 50 cm in a normal year.
7. Increased runoff and water tables may have on site and off site effects, and can be positive or negative for environmental concerns. Negative effects may include hindering mechanical operations and free regeneration, disturbance of wildlife habitats, and acceleration of mineralization and solute/contaminant transport processes. Increased groundwater recharge and stream flow are beneficial to on-site or downstream users during the dry seasons.
8. Insufficient information about the poorly-defined watershed boundaries, both in lateral and vertical directions, decreases the accuracy of water balances and increases the uncertainty of model outputs for the net groundwater flow, the surface flow and the deep seepage. More measured data for the post treatment period at the Gator

Nationals Forest site are needed to test the model performance in this respect.

Recommendations for Additional Research

Field Research

The present study represented a very comprehensive study of its kind, and in collaboration with other studies on the same site provided valuable field data for flatwoods hydrologic models development to understand pine flatwoods ecosystems. However, due to the low topographic gradients in the pine flatwoods landscape, the integrity of watershed boundaries is poorly defined. Significant errors might occur in the measurement of surface inflows and outflows even in a single wetland system. Future research should pay more attention to pathways of the surface flow to better establish watershed water budgets.

A recently completed project funded by the U. S. Forest Service studied the evapotranspiration processes in undisturbed cypress wetlands and pine uplands at the Gator Nationals Forest site (Riekerk et al., 1995). Unfortunately, this project covered only the pre-treatment period. Forest harvesting practices significantly alter the energy/water balance and evapotranspiration processes in forest ecosystems. There are no measurements yet on the soil evaporation component, which presumably is a significant water loss from the post-treatment site. Additional studies are needed to quantify the difference in evapotranspiration from forested and harvested and regenerated flatwoods at the same time. These kinds of data would be very useful to establish water and energy balances for disturbed ecosystems. Also, the data are needed for further calibration and verification of the FLATWOODS model.

The IMPAC project has proved to be a successful program for forest ecosystem

management in the southeastern region. Long-term hydrologic and water quality data from three experimental watersheds are being synthesized (Riekerk, personal communication). The control watershed, which has been used throughout this dissertation study, is recommended for future studies herein. Common forest practices used by the forestry industry may be applied to this watershed to study the hydrologic effects as well as other biological perturbations in this 55-year old forest. This proposed study would offer an unique, cost-effective opportunity to study a single treatment impact on the flatwoods ecosystem since pre-treatment data have been collected for eighteen years. Most important, the measurements on the hydrologic variables would provide an excellent data set to calibrate and verify the new FLATWOODS model.

Modeling Research

The new FLATWOODS forest hydrological simulation model provides an alternate tool to study the pine flatwoods hydrology. As any other existing watershed scale hydrological model, the predictability of the present model is heavily dependent on field testing with measurement data. Computer simulation models cannot replace the field experimentation, but rather they are complementary means to achieve the same goals.

Two algorithms in the FLATWOODS model are the least physically-based, one is the deep seepage equation and the other is the surface flow routing equation. With increasing knowledge of the relationship between the surficial aquifer and the lower aquifer, a Darcian method could be introduced into the model. The cell-by-cell surface flow routing method by the ANSWERS model (Beasley and Huggins, 1982; Thomas, 1989; Montas and

Madramootoo; 1991) was not used in the present model to reduce model complexity. But, this simplification could increase the uncertainty in the runoff simulation. The FLATWOODS model could be improved by using physically based surface flow routing procedures as more digital topographical data are available and data management becomes easier with the aid of geographical information systems (GIS).

The model has been calibrated with areal average groundwater table elevations for the entire area of the Gator Nationals Forest site. Further verification with more spatial measurements (e.g., individual block or wetland-upland system) are needed for future studies. The three extensively-monitored NCASI wetlands could be used as a small-scale detailed test for the model since daily water table and runoff data are available.

Being a distributed watershed scale model, the FLATWOODS model needs detailed spatially distributed process parameters (e.g., surface elevation, vegetation, soils) and climate data as model inputs. These data are normally not readily available or difficult to get for large areas. In addition, model outputs from watershed-scale models like FLAWTOODS are difficult to interpret for users without training in computer modeling. The GIS technique shows promise to combine spatial watershed information and spatial analysis functions with distributed hydrologic models, and GIS are the future of pre- and post-processors of large scale models (Sebhat et al., 1995).

APPENDICES

Appendix A. Groundwater Maps for C, K and N Wetlands of 1993-1994.

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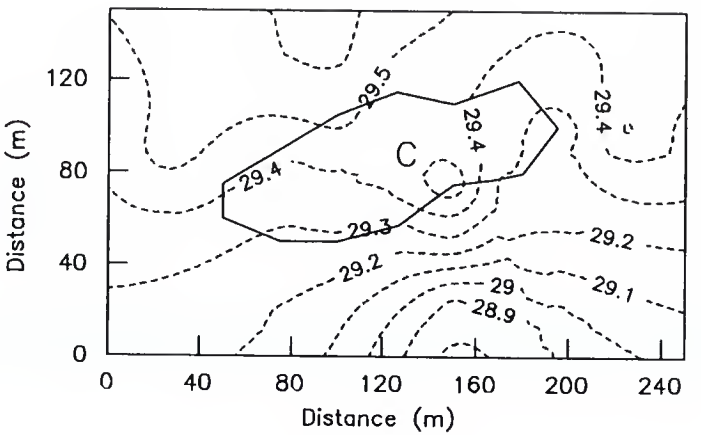

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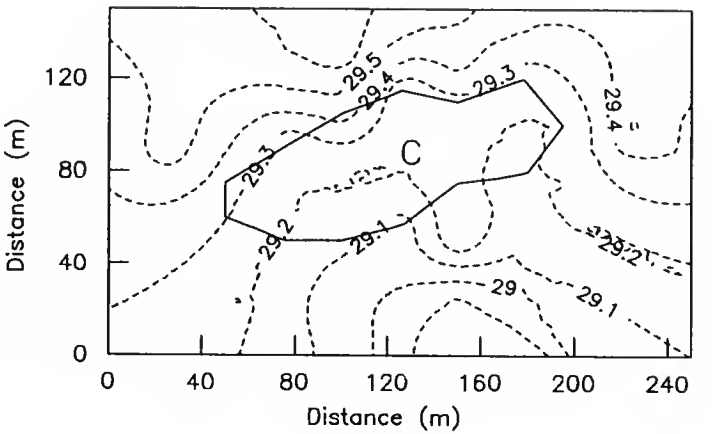

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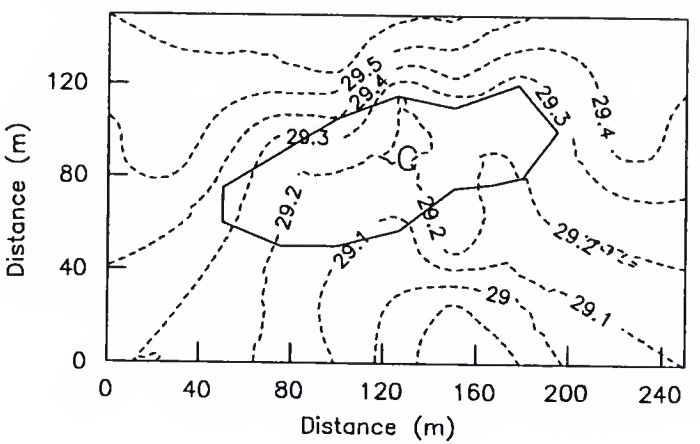

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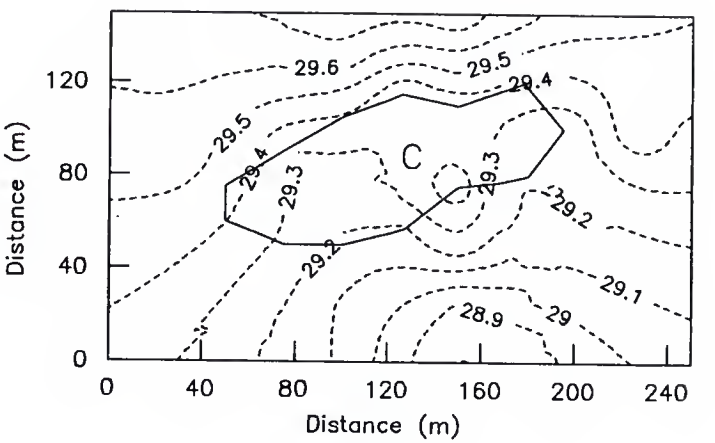

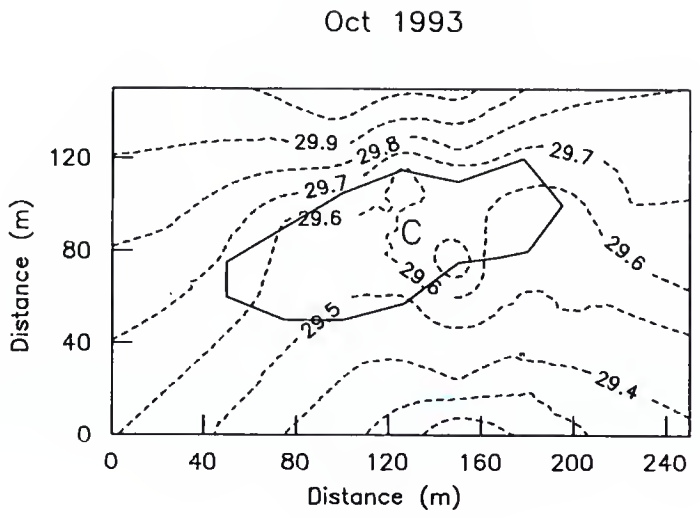
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29.7
29.6
29.5
29.4
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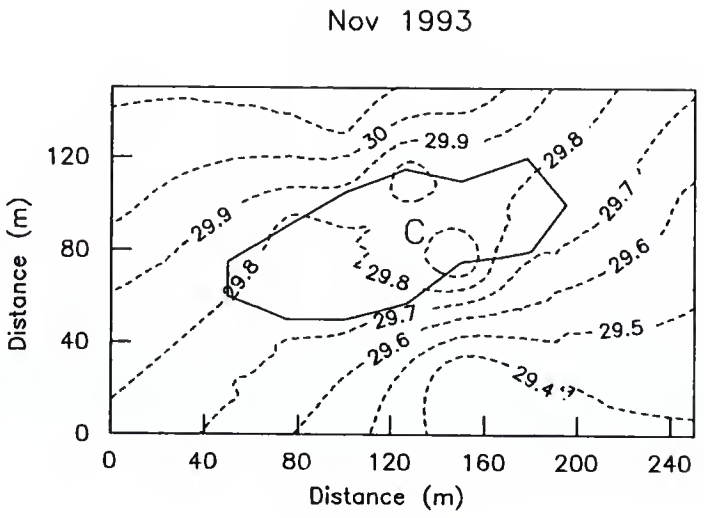
80
120
160
200
240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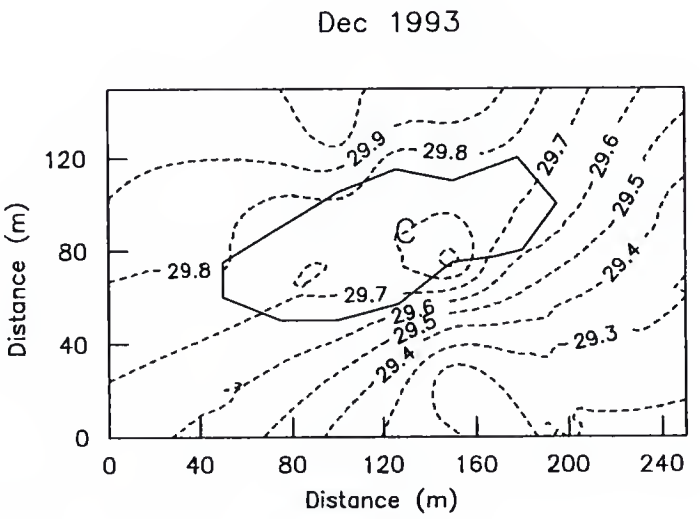
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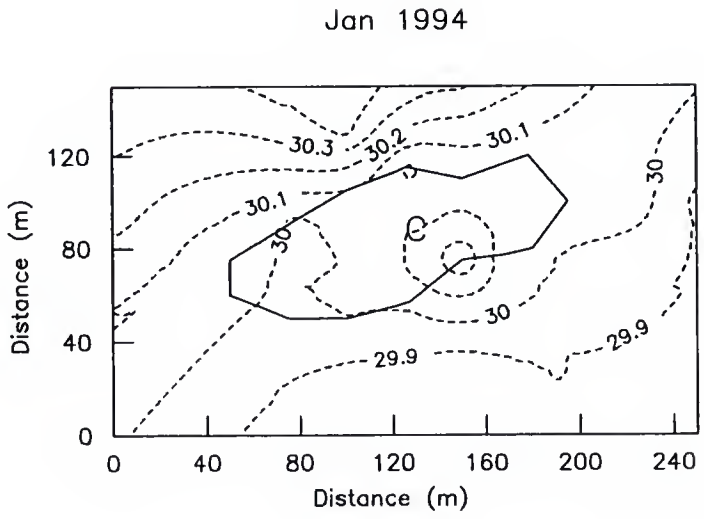
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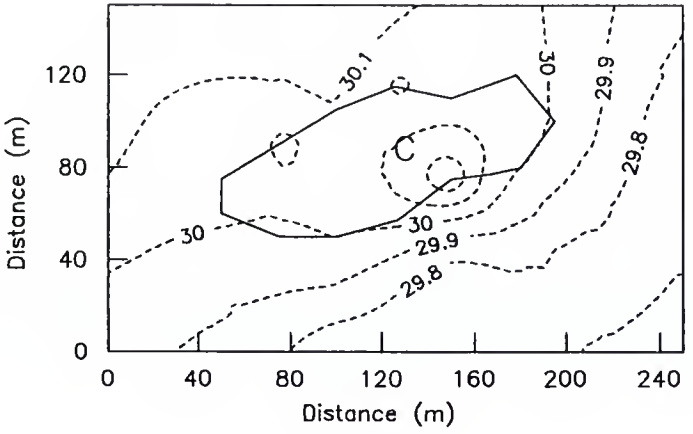
Feb 1994



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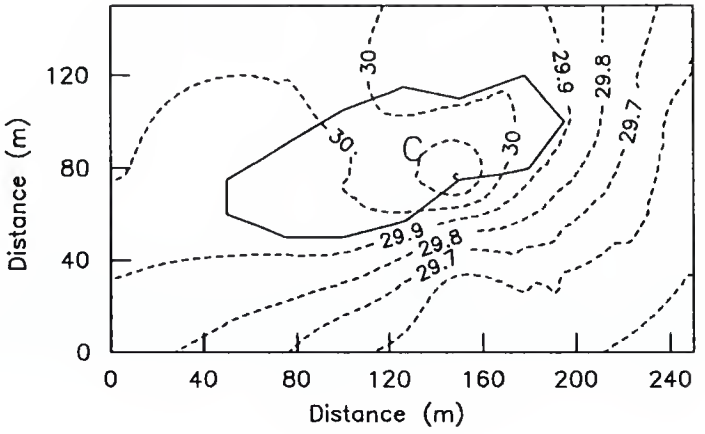

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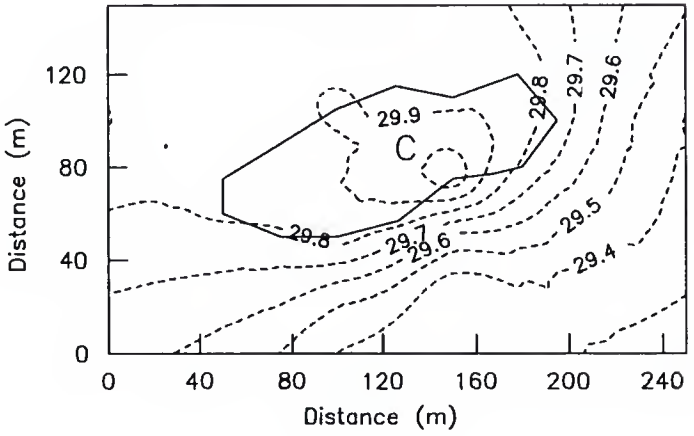

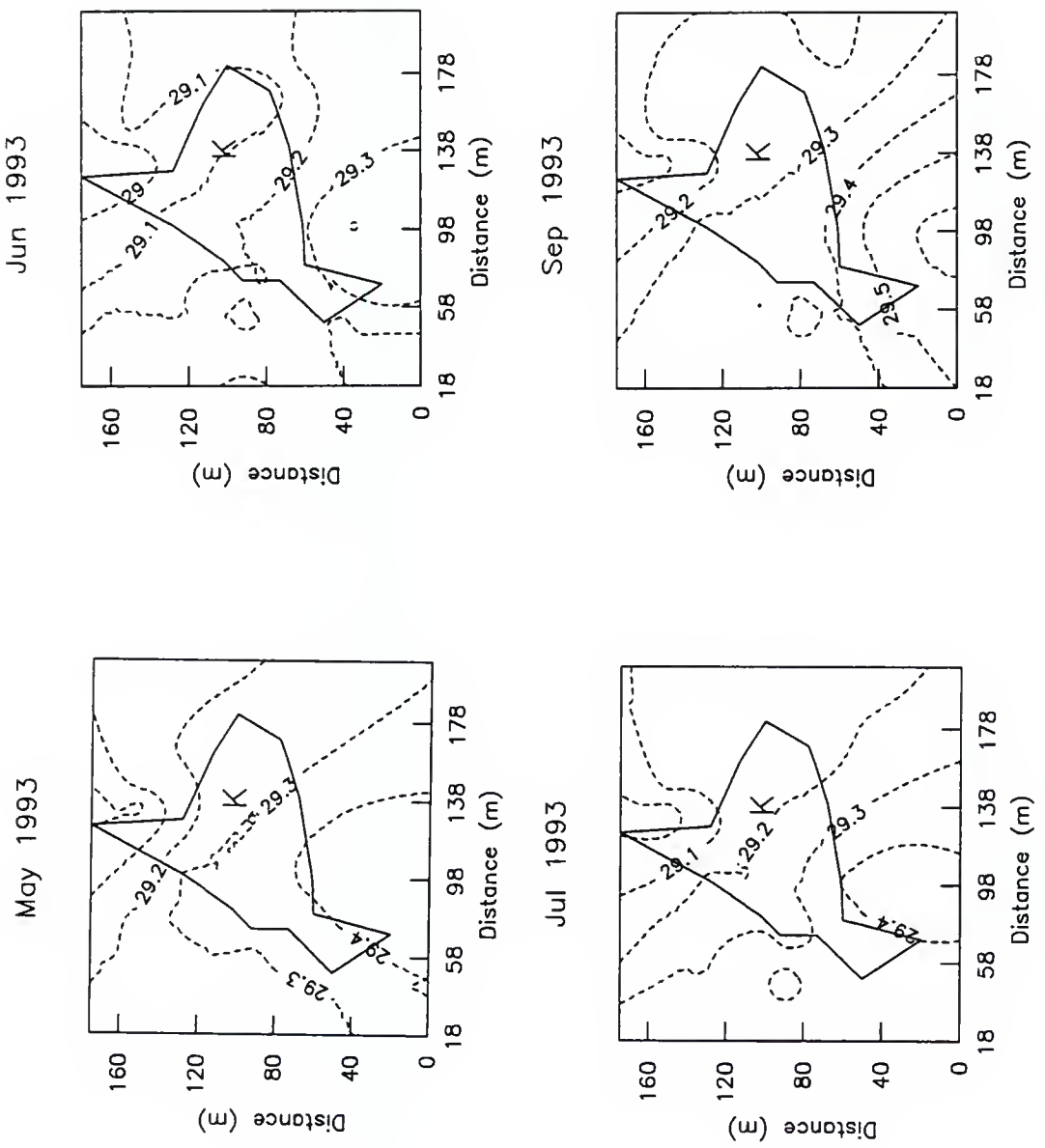
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29
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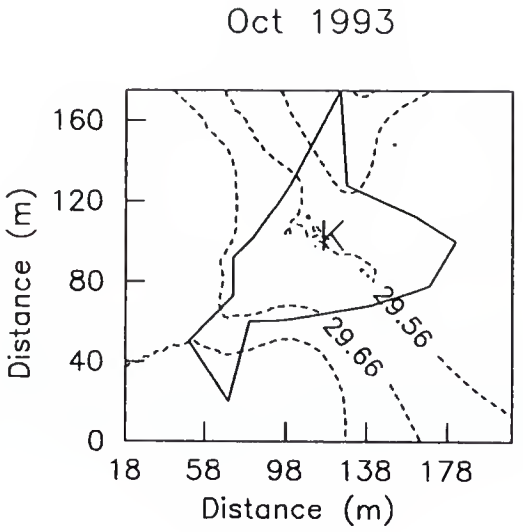
29.3
29.4
29.5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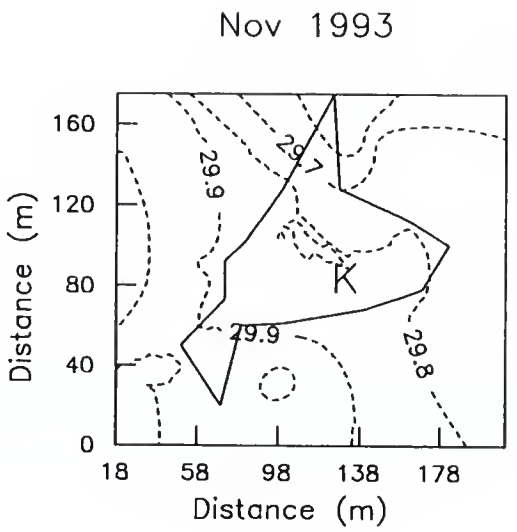
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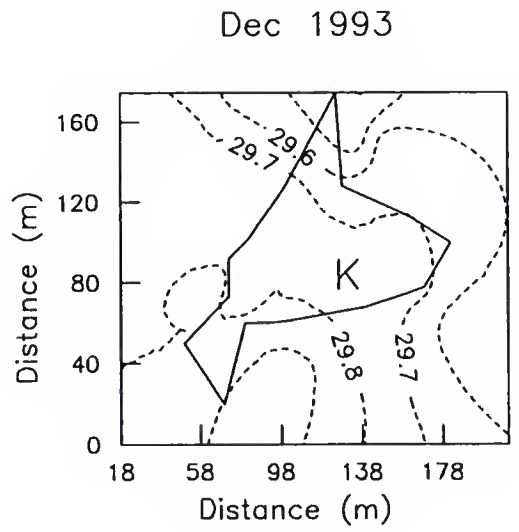
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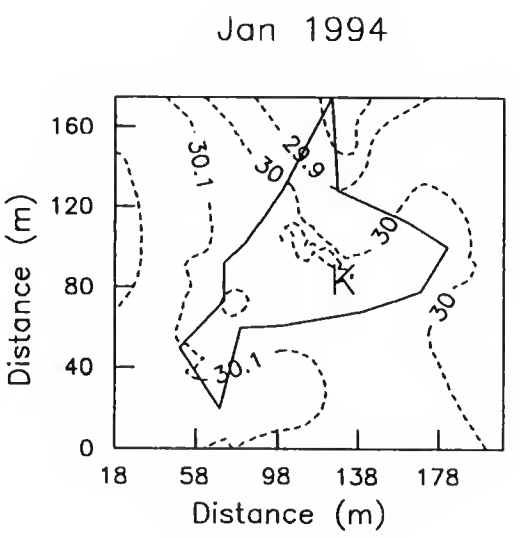
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30.1

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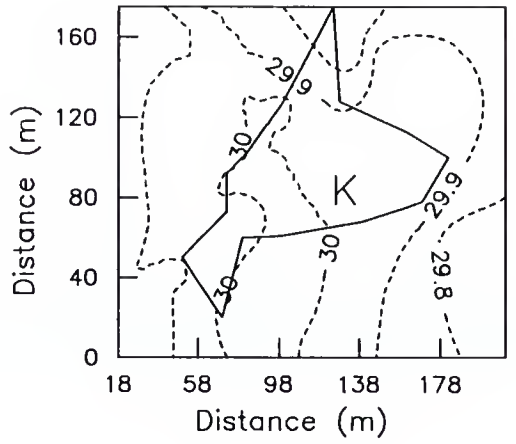

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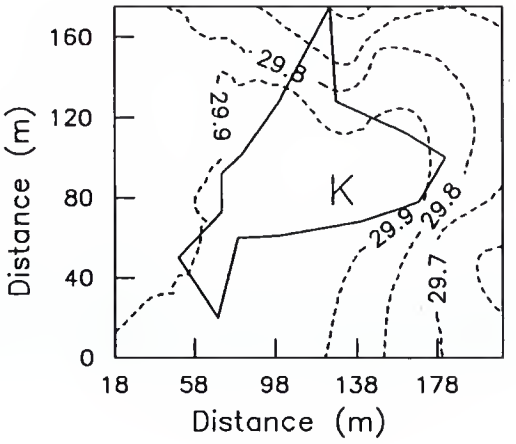

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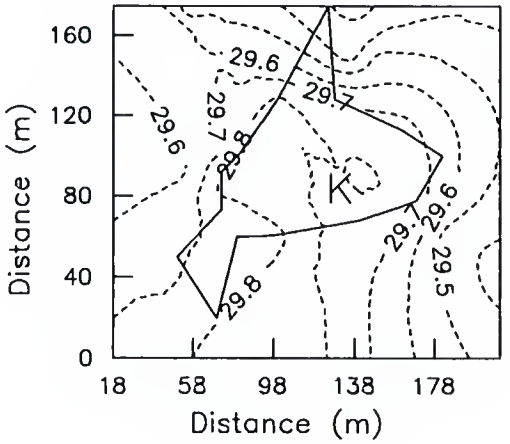

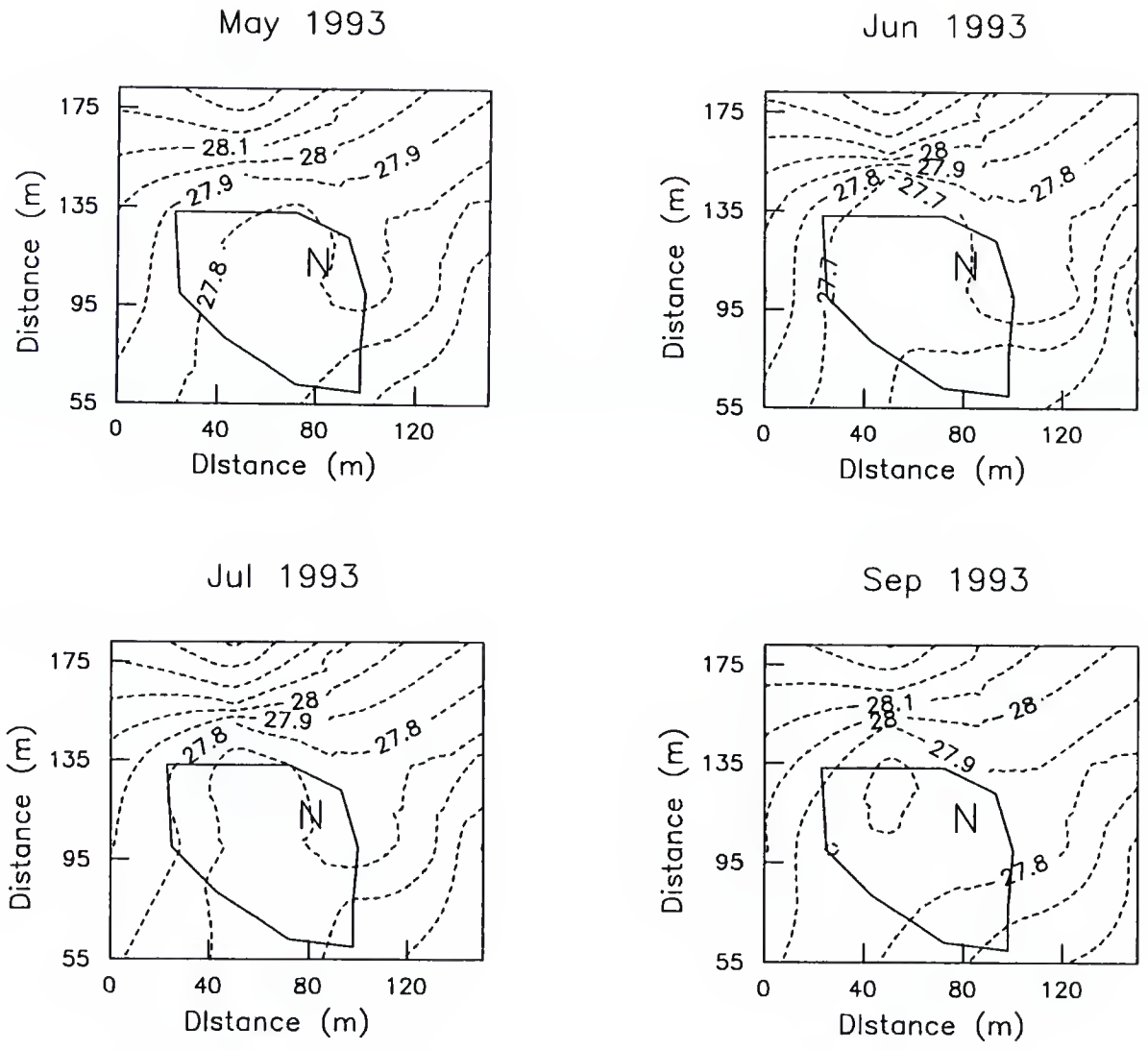
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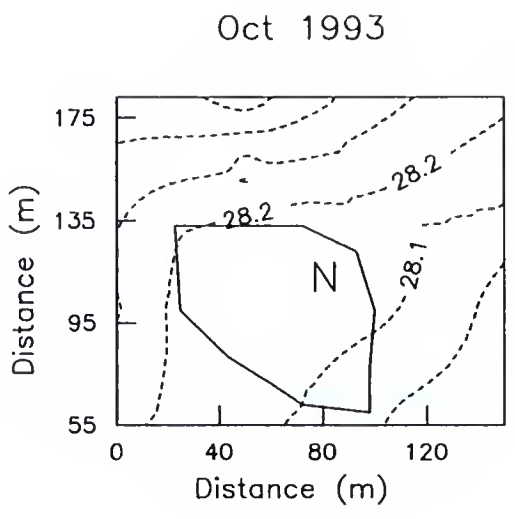
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80
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Distance (m)
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28.2
28.1
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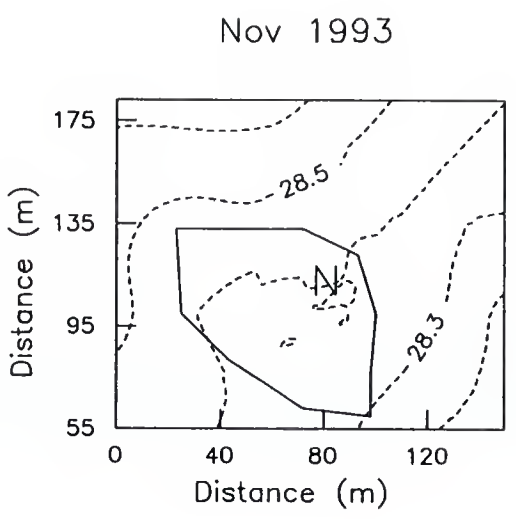
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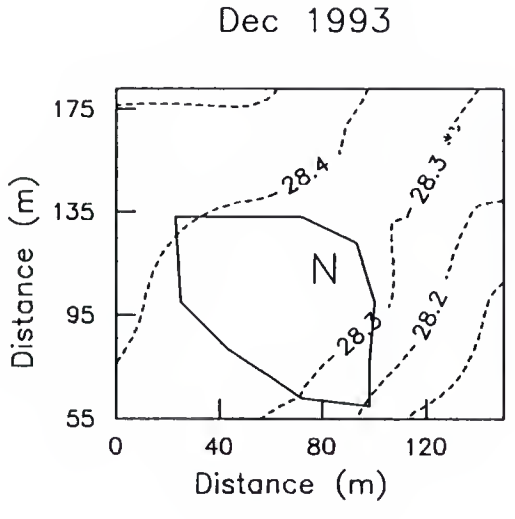
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120
Distance (m)
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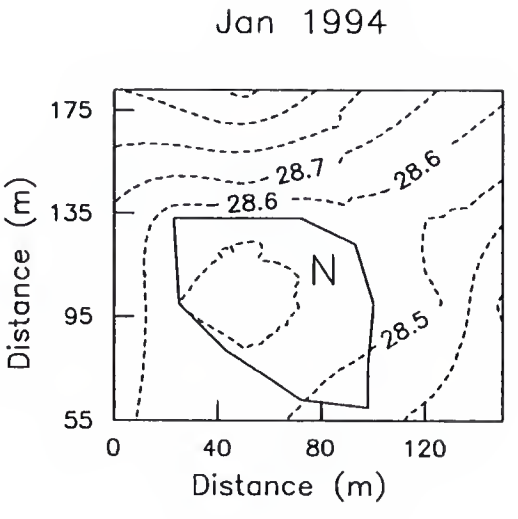
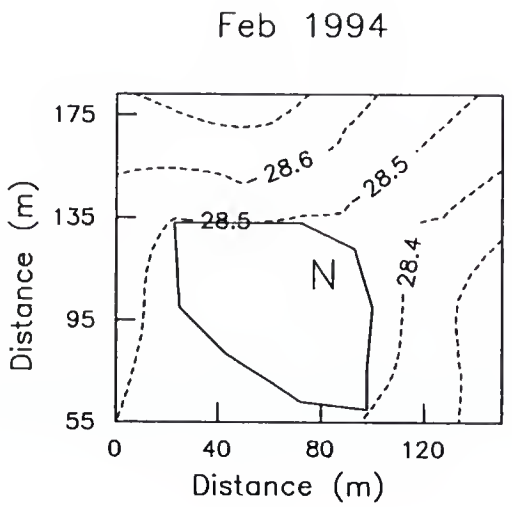
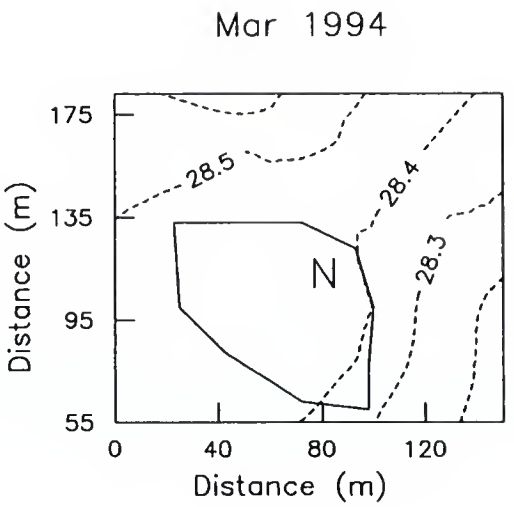
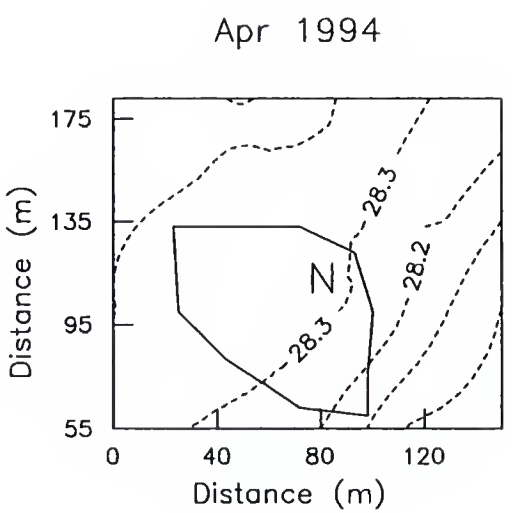
28.3
28.2
N


Jan 1994
175
135
95
55
Distance (m)
0
40
80
120
Distance (m)
28.7
28.6
28.6
28.5
N


Feb 1994
175
135
95
55
Distance (m)
0
40
80
120
Distance (m)
28.6
28.5
28.5
28.4
N


Mar 1994
175
135
95
55
Distance (m)
0
40
80
120
Distance (m)
28.5
28.4
28.3
N


Apr 1994
175
135
95
55
Distance (m)
0
40
80
120
Distance (m)
28.3
28.2
28.3
N

Appendix B. Listing of the FLATWOODS Model Source Code.

The FLATWOODS model source code is a modified version of the COASTAL program (C-H. Sun, 1985). The COMMON block was written and added to the original code by the author of this dissertation. Other subroutines have been modified in different degrees. Specific descriptions can be found in the text portion of this dissertation. In most cases, alteration of the original code has been indicated by lower case in this program listing.

```
      COMMON/X/ X(10000)
      COMMON/SHR/ IBOUND(30,30),W(50)
      COMMON/BASIC/ INRPS,IUNIT(12),MDAY(12),YEAR,IYEAR,iout,
     >          NCELL,NCOL,NROW,NLAY,NODES,TOTIM,DEGLAT,PEC
      INTEGER YEAR

      COMMON/LOCATE/ LCHOLD,LCHNEW,LCSTRT,LCDELR,LCDELC,LCSC1,
     >          LCHY,LCBOT,LCTOP,LCCC,LCCR,LCCV,LCUZDE,
     >          LCHCOF,LCRHS,lcuzone1,lcuzone2,lcuzone3
      COMMON/LAND/LADUSE(200,6),lid(200),cele(200),irow(200),icol(200)
      real laduse,cele
      integer irow,icol

      COMMON/DAY/ IM,ILM,IDD,IMONTH
      COMMON/BUDGET/PRECIP(366),PE(200),PT(200),PET(366),
     >          PINT(200),WFLOW(366),UDRAIN(200),UZONE(200),AE(200),
     >          AT(200),AET(200),GFLOW(366),GDRAIN(200),REFLOW(366),
     >    GGFLOW(366),SINT(200),EVPT(200),sae(366),sat(366),sevpt(366),
     >          LEAK(200), MID(366),MWT(366)
      integer MID
      real leak,MWT

      COMMON/AREA/ TAREA,TWAREA,area(200),tuarea
      real tarea,twarea,tuarea,area

      COMMON/lai/ lai(5,366),mlai(5,366),Clai(5)
      real lai,mlai,clai

      COMMON/SURF/ LAYER,ilayer,ilt,CE1,CE2,CT1,CT2,CET,WEIGHT(5,5),
     > trd(5,5), mtrd(5,5),ttrd(5),tmtrd(5)
      Real mtrd

      COMMON/IDX/ PLAYER(200)
      COMMON/SOIL/ssmc(5,5),KS(5,5),wa(5,5),wn(5,5),
     >wb(5,5),wc(5,5),wm(5,5),FC(5,5),RSMC(5,5)
      REAL ssmc,KS,wa,wn,wb,wc,fc,rsmc

      COMMON/SGF/ DELT,NSTP,PERTIM,TRPY,KITER,HCNV,ILEVEL,
     >          KSTP,KPER,NRIVER,MXITER,NPARM,
     >          HCLOSE,ACCL,IPCALC,IPRSIP,IPRSOR,
     >          NSLICE,MBW,ISTRT

      Common/head/ sy(16,15),CKS3(10),DELR(20),DELC(20),
     >          BOT(16,15),TOP(16,15), CV(20,20)

      COMMON/RAIN/ RAIN(366,3),DIST(200,3),NSTA
      integer nsta

      COMMON/FLAG/ IFLAG

      COMMON/STREAM/K1,K2,K3,Lc
      real K1,K2,K3,Lc

      COMMON/UZON/smc1(200),smc2(200),smc3(200),uuzone1(200),
     > uuzone2(200),uuzone3(200)
      real smc1,smc2,smc3,uuzone1,uuzone2,uuzone3

      COMMON/SIMULA/ SIFLOW(366),SAET(366),SUDRAIN(366),SUZONE(366),
     >          SAHNEW(366),SSINT(366),HPREC1(366),Sleak(366)
      Common/data/ indexwt, indexrun
      Common/top/atop

$NOFLOATCALLS
$STORAGE:2
```

```
$debug

    PROGRAM FLATWOODS
$include:'com.for'

C --- Write introductory information to screen

  WRITE(*,10)
  10 FORMAT(//,
    >'~~~
```

```
      OPEN(100,FILE='temp.prn',STATUS='unknown')
      open(120,file='contour.out',status='unknown')
C
C --- Basic output unit number
      IOUT=77
C
C --- Input unit for module COARPS
      INRPS=1
      ICY=0
C
C --- Read and prepare data for a simulation
      CALL COARPS

C --- Start simulation
      DO 200 IY=1,IYEAR
         ICY=ICY+1
C
C ---   Read daily precipitation and daily temperature data
C ---   for a year and also calculate daily potential
C ---   evapotranspiration
        CALL COAATM(IBDAY, ICY)
C
C ---   Initialize counter
        IDAY=0
C
C ---   Simulate water budget for a year
        DO 100 IM=1,ILM
        IMONTH=IM
        ICOUNT=0

C ---     Simulate water budget for a month
          DO 70 IDd=1,MDAY(IMONTH)
            IDAY=IDAY+1

C ---       Check the beginning simulation day
            IF(IDAY.LT.IBDAY) GO TO 70
            ICOUNT=ICOUNT+1
C
C ---       Simulate rainfall interception
            CALL COAINT(IDAY)

C ---       Simulate unsaturated ground water flow (4.0)

            CALL COAUSF(IDAY,X(LCHNEW),X(LCHOLD),ibday, icy,
     >       X(LCuzone1),X(LCuzone2),X(LCuzone3) )

            CALL COAAET(IDAY,X(LCHNEW),X(LCuzone1),X(LCuzone2),
     >       X(LCuzone3) )
C ---       Simulate saturated ground water flow
            CALL COASGF(IDAY)
C
C ---       Calculate daily water budget and write to file
C ---       "DAILY.OUT".
          CALL COADAY(IDAY,X(LCHNEW), X(LCuzone1),X(LCuzone2),
     >     X(LCuzone3))
 70       CONTINUE
        IF  (ICOUNT.EQ.0)  GO TO 100
C
C ---   Calculate monthly water budget
        CALL COABUG(ICOUNT,IDAY,1)
 100    CONTINUE
C
C --- Calculate yearly water budget
      CALL COABUG(IBDAY,IDAY,2)
 200 CONTINUE
```

```
      STOP
      END
C*************************************************************************C
C   1.0                                    C
C   *** SUBROUTINE COARPS ***                          C
C   This module calls each read and prepare module in sequence      C
C   and also allocate space in X array for ground water flow        C
C   simulation                                  C
C                                          C
C*************************************************************************C
      SUBROUTINE COARPS

$include:'com.for'

C --- Define and set key model parameter
      CALL RPSDF
C
C --- Read and prepare data for module COAINT
      CALL RPSINT
C
C --- Read and prepare data for mudule COAAET
      CALL RPSAET
      isum=50
      isum = isum+Ncell
      Lcuzone1=isum
      Isum=isum+ncell
      Lcuzone2=isum
      Isum=isum+ncell
      Lcuzone3=isum
      ISUM=Isum+Nrow*Ncol
C
C --- Allocate space for the COAUSF module

C --- Read and prepare data for mudule COAUSF
      CALL RPSUSF
C
C --- Allocate space for the COASGF module

      LCHOLD=ISUM
      ISUM=ISUM+(NROW*NCOL)
      LCHNEW=ISUM
      ISUM=ISUM+(NROW*NCOL)
      LCSTRT=ISUM
      ISUM=ISUM+(NROW*NCOL)
C --- Read and prepare data for module COASGF

      CALL RPSSGF (X(LCHOLD),X(LCHNEW),X(LCSTRT))
C
C --- Allocate space for the SGFBCF module

      LCDELR=ISUM
      ISUM=ISUM+NCOL
      LCDELC=ISUM
      ISUM=ISUM+NROW
      LCSC1=ISUM
      ISUM=ISUM+(NROW*NCOL)
      LCHY=ISUM
      ISUM=ISUM+(NROW*NCOL)
      LCBOT=ISUM
      ISUM=ISUM+(NROW*NCOL)
      LCTOP=ISUM
      ISUM=ISUM+(NROW*NCOL)
      LCCC=ISUM
      ISUM=ISUM+(NROW*NCOL)
      LCCR=ISUM
```

```
      ISUM=ISUM+(NROW*NCOL)
      LCCV=ISUM
      ISUM=ISUM+(NROW*NCOL)
      LCHCOF=ISUM
      ISUM=ISUM+(NROW*NCOL)
      LCRHS=ISUM
      ISUM=ISUM+(NROW*NCOL)
C
C --- Read and prepare data for module SGFBCF
      CALL RPSBCF (X(LCCC))
C
C --- Read and prepare data for module SGFSIP
      IF(IUNIT(7).GT.0) CALL RPSSIP
C
C --- Read and prepare data for module SGFSOR
      IF(IUNIT(8).GT.0) CALL RPSSOR
C
C --- Return
      RETURN
      END

$NOFLOATCALLS
$STORAGE:2
$debug
C*************************************************************************C
C   1.1                                 C
C   *** SUBROUTINE RPSDF ***                          C
C   Define the geometry of the simulated watershed and set up      C
C   FORTRAN unit number for each input file                C
C                                       C
C*************************************************************************C
      SUBROUTINE RPSDF
      CHARACTER*4 HEADNG(20)
      CHARACTER*6 MODULE(12)
$include:'com.for'

      DATA MODULE/'COARPS','COAINT','COAAET','COAUSF',
     >       'COASGF','SGFBCF','SGFSIP','SGFSOR',
     >       'RESERV','COAATM','    ','    '/
C
C --- Print the name of the program
      WRITE(IOUT,2000)
 2000 FORMAT(1H1/,23X,'COASTAL -- A DISTRIBUTED SURFACE WATER/',
     > 'GROUND WATER HYDROLOGIC SIMULATION MODEL',//,
     > 52X,'VERSION 1.1   SEPTEMBER 1985'////)
C
C --- Read and print a heading
      READ(INRPS,1000) HEADNG
 1000 FORMAT(20A4)
      WRITE(IOUT,2010) HEADNG
 2010 FORMAT(' ',20A4/)
C
C --- Read watershed latitude and PE correction factor (PEC)
      READ(INRPS,1010) DEGLAT,PEC
 1010 FORMAT(2F10.2)
C
C --- Read number of rows, columns, number of active cell,
C --- and number of years to be simulated
      READ(INRPS,1020) NROW,NCOL,Ncell,IYEAR
 1020 FORMAT(8I10)
C
C --- Print # of rows, columns, and simulation periods
      WRITE(IOUT,2020) NROW,NCOL,Ncell
 2020 FORMAT(/' Cell FORMAT: ',I5,' ROWS',I5,' COLUMNS'//,
     > I5,' ACTIVE Cells WITHIN THE WATERSHED'/)
```

```
      WRITE(IOUT,2030) IYEAR
 2030 FORMAT(I5,' YEARS TO BE SIMULATED'///)
C
C --- Read and print input unit numbers (IUNIT) used by
C --- major modules
      READ(INRPS,1030) IUNIT
 1030 FORMAT(1213)
      WRITE(IOUT,2040)
 2040 FORMAT(' INPUT UNITS:')
      DO 10 I=1,10
        IF(IUNIT(I).LE.0) GO TO 10
        WRITE(IOUT,2050) MODULE(I),IUNIT(I)
 2050   FORMAT(' INPUT DATA FOR MODULE ',A6,' IS READ',
     >       ' FROM UNIT #',I2)
   10 CONTINUE
C
C --- Initialize total elapsed time counter and calculate
C --- number of cells
      TOTIM=0
      NLAY=1
      NODES=NCOL*NROW*NLAY
C
C --- RETURN
      RETURN
      END
C*******************************************************************************C
C    1.2                                    C
C    *** SUBROUTINE RPSINT ***                          C
C    Read and prepare data for mudule COAINT              C
C                                          C
C*******************************************************************************C
      SUBROUTINE RPSINT

$include:'com.for'

C --- Input unit number
      IN=IUNIT(2)
C
C --- Read and print land use data for each active cell
      WRITE(IOUT,2000)
 2000 FORMAT(1H1,/' LANDUSE INFORMATION IN PERCENTAGE',
     >      ' FOR EACH ACTIVE Cell',//,
     >      ' Cell NUM.   PINE     WETLAND  Landuse Index',
     >      '    AREA    ROW    COLUMN
     >   Critcal Ele')
C
C --- Initialize TAREA and TWAREA
      TAREA=0.
      TWAREA=0.
C
C --- Input landuse and area data for each cell
       Read (in,900) ilt
 900     format (I8)

      DO 10 I=1,Ncell

       READ(IN,1000) Icell,(LADUSE(I,K),K=1,ilt),Iid(I),
     >  area(I),IROW(i),ICOL(i),CELE(I)
 1000   FORMAT(I8,2F8.2,I8,F8.6,2I8,F13.3)

       If (Iid (i) .eq. 1) then
       Cele(i)=Cele(i)-0.150
       endif

       TAREA=TAREA+area(I)
```

```
      TWAREA = TWAREA+(LADUSE(I,2)*0.01)*area(I)
      WRITE(IOUT,2005)ICell,(LADUSE(I,K),K=1,ilt),lid(I),area(i),
     >  IROW(i),ICOL(i),cele(I)
 2005   FORMAT(I10,2F10.2,I10,F10.6,2I10, F10.3)
  10 CONTINUE
     Tuarea = tarea-twarea
     WRITE(IOUT,2010) TAREA,TWAREA, TUarea, ilt
 2010 FORMAT(//' TOTAL AREA FOR THE SIMULATED WATERSHED =',F10.2,
     >     ' KM2'//,' TOTAL WETLAND AREA FOR',
     >     ' THE SIMULATED WATERSHED =',F10.2,'  KM2'/,
     >     ' Total Pine Upland Area = ',F10.2, '  KM2'/,
     >     ' Total land use types =',I2 )

C    read data of lai coefficient assuming stands of different age have
C    the same distribution of LAI vs. t.

     Read (in, 2020) (CLAI(i),i=1,ilt)
 2020  format (2F10.1)

     write (iout, 2030)(clai(i),i=1,ilt)
 2030  format ('conversion coefficients for LAI from standard'/,2F10.1)

C --- RETURN
     RETURN
     END
C*************************************************************************C
C    1.3                                  C
C    *** SUBROUTINE RPSAET ***                        C
C    Read and prepare data for module COAAET            C
C                                         C
C*************************************************************************C
     SUBROUTINE RPSAET
$include:'com.for'

C --- Input unit number
     IN=IUNIT(3)
C --- read in number of layers for unsaturated water flow routing
     Read (in,900) ilt, ilayer
 900   format (2I10)
C --- Read ROOT DENSITY AND CALCULATE transpiration weighting factors WEIGHT(I)

     Do 45 I=1, ilt
C --- raed in root density of mature forests (mtrd) and of the lands simulated(trd)
C --- and calculate weighting factors for distributing transpiration for each layer.
     td=0.
     tmd=0.

     do 40 j=1,ilayer
     read (in, 1000) mtrd(i,j),trd(i,j)
     tmd=tmd+mtrd(i,j)
     td=td+trd(i,j)
 1000  FORMAT(2F10.1)
 40   continue

     tmtrd(i) = tmd
     ttrd(i) = td
 45   continue

     do 50 I=1,ilt
     write (iout,1200) i
     do 50 j=1,ilayer

     Weight(i,j) = trd(i,j)/ttrd(i)

     write (iout,1300) j, mtrd(i,j), trd(i,j),weight(i,j)
```

```
50   continue

1200  format (//'Land Use :   ',I2,/,18x,'MTRD',7x,
   >'TRD',7x,'Weight')

1300  FORMAT(' Layer #  ',i2,2F10.1,f10.3)


C --- Read model parameters for module COAAET. CE1 and CE2 are parameters for estimating
C --- soil evaporation; CT is coefficient for estimating transpiration; CET is a parameter
C --- to account for upward water flow;
    READ(In,1010) CE1,CE2,CT1,CT2,CET
 1010 FORMAT(5F10.2)
    WRITE(79,2010) CE1,CE2,CT1,CET
    WRITE(IOUT,2010) CE1,CE2,CT1,CT2,CET
 2010 FORMAT(/,'EVAPORATION REDUCTION PARAMETER DUE TO SHADING (CE1): ',
   >     F10.2,/'EVAPORATION REDUCTION PARAMETER (CE2): ',f10.2,/,
   >    'LAI conversion factor for shrubs (CT1): ', f10.2,/,
   >    'TRANSPIRATION REDUCTION PARAMETER (CT2):  ',F10.2,/,
   >    ' SOIL MOISTURE CONTENT REDUCTION PARAMETER =',F10.2/)

     READ(IN,1020) K1,K2,K3,Lc
1020   FORMAT(3F10.3,F10.3)

     write (iout,2050) K1,K2,K3,Lc
2050   FORMAT(' Parameters to calculate stream runoff by
   > Q=K1*Exp(K2*A)-K3'/,
   > 'Coefficient K1:', F8.3,/'Coefficient K2:',F8.3,
   > 'Coefficient K3:', F8.3,/'Coefficient for Groundwater Leakage
   >by: Leakout= Lc*(H-bot)**2: ', F8.3)

    RETURN
    END
C*************************************************************************C
C    1.4                                    C
C    *** SUBROUTINE RPSUSF ***                          C
C    Read and prepare data for module RPSUSF             C
C                                          C
C*************************************************************************C
    SUBROUTINE RPSUSF
    CHARACTER ANAME(6,2)*4

$include:'com.for'

    DATA ANAME(1,1),ANAME(2,1),ANAME(3,1),ANAME(4,1),ANAME(5,1),
   >ANAME(6,1)/'    ','    ','  FI','ELD ','CAPA','CITY'/
    DATA ANAME(1,2),ANAME(2,2),ANAME(3,2),ANAME(4,2),ANAME(5,2),
   >ANAME(6,2)/'    ','    ','  W','ILTI','NG P','OINT'/
C
C --- Input unit number
    IN=IUNIT(4)

C --- Read initial moisture contents of unsaturated zone

    do 30 I=1,ilt
    do 30 J=1,ilayer
    READ(IN,1000) ks(i,j), ssmc(i,j),rsmc(i,j),fc(i,j),wa(i,j),
   > wb(i,j),wn(i,j)
 1000 FORMAT(4F10.2, F10.4, F10.3,F10.2)
    wc(i,j)=-1+1/wb(i,j)
    Wm(i,j)=1-1/wn(i,j)
  30  continue
C  40  continue

C --- Write to output files
```

```
      do 80 I=1,ilt
      WRITE(Iout, 2040) I
 2040 format(/,'Landuse No.',I10,/,
     >'          Ks       SSMC      RSMC      FC       Wa
     >  Wb       Wn ')

      do 80 J=1, ilayer

2020  FORMAT('Layer No.', I3, 4F10.2, F10.4, 2F10.3, F10.2)
      write (IOUT,2020) J, ks(i,j), ssmc(i,j),rsmc(i,j),fc(i,j),
     >wa(i,j),wb(i,j), wn(i,j)

80    continue


C --- Initialize EVP, and SINT array
C --- UZONE1, and UZONE2 arrays

      DO 10 I=1,Ncell
       EVPT(I)=0.
       SINT(I)=0.
 10   CONTINUE

C
C --- Return
      RETURN
      END
C*************************************************************************C
C    1.5                                        C
C    *** SUBROUTINE RPSSGF ***                          C
C    Read and prepare data for module COASGF              C
C                                              C
C*************************************************************************C
      SUBROUTINE RPSSGF (Hold,Hnew,strt)

      CHARACTER ANAME(6,1)*4

$include:'com.for'

      dimension hold(ncol,nrow),hnew(ncol,nrow),strt(ncol,nrow)

      DATA ANAME/'  ','  ','  S','TART','ING ','HEAD'/
C
C --- Input unit number
      IN=IUNIT(5)

C
C --- Calculate number of cells in a layer
      NCR=NCOL*NROW
C
C --- Initialize IBOUND array
      DO 5 I=1,NROW
      DO 5 J=1,NCOL
    5 IBOUND(J,I)=0
C
C --- Read boundary array (IBOUND)
      WRITE(IOUT,2000)
 2000 FORMAT(1H1,//' BOUNDARY ARRAY :'/,
     >          '    1 = VARIABLE HEAD CELL'/,
     >          '    0 = NO FLOW BOUNDARY CELL'/,
     >          '   -1 = CONSTANT GRADIENT BOUNDARY CELL'/)
      DO 10 I=1,NROW
        READ(IN,1000) (IBOUND(J,I),J=1,NCOL)
 1000   FORMAT(2513)
        WRITE(IOUT,2010) (IBOUND(J,I),J=1,NCOL)
```

```
 2010   FORMAT(2513)
  10 CONTINUE
C
C --- Read time steps for each stress period (NSTP),
C --- length of time step (DELT), ISTRT flag (1= save start
C --- head, 0= not to save start head), and ILEVEL flag
C --- (1= daily ground water level for each cell will be written
C --- to a disk file "WLEVEL.OUT", 0= daily ground water level
C --- will not be saved).
     READ(IN,1010) NSTP,DELT,ISTRT,ILEVEL
 1010 FORMAT(I10,F10.1,2I10)
     WRITE(IOUT,2030) NSTP,DELT
 2030 FORMAT(/,' TIME STEPS FOR EACH STRESS PERIOD (ONE DAY) =',I5,/
    >     ' LENGTH OF EACH TIME STEP =',F5.2,' DAY')
C
C --- Read starting head

     CALL U2DREL(HOLD,ANAME(1,1),NROW,NCOL,IN,IOUT)

     write (iout,2040)
2040  format (10x,/,'Initial Water Table Elevation (m) '/)

     DO 20 I=1,NROW
     write (iout,2050) i,(hold(j,i),j=1,ncol)
  20 CONTINUE
2050  format (I5,20F10.3)

C --- Copy initial heads from HOLD to HNEW

     do 50 I=1, nrow
     do 50 j=1, ncol
     hnew(j,i)=hold(j,i)
50    continue

C --- If starting heads are to be saved then copy HOLD to STRT
     IF(ISTRT.NE.0) THEN
       WRITE(IOUT,2035)
 2035   FORMAT(/' STARTING HEAD WILL BE SAVED')
       DO 30 I=1,NROW
       DO 30 J=1,NCOL
         STRT(J,I)=HOLD(J,I)
  30   CONTINUE
     ELSE
       WRITE(IOUT,2055)
 2055   FORMAT(/' STARTING HEAD WILL NOT BE SAVED')
     ENDIF

C
C --- Return
     RETURN
     END
C-----------------------------------------------------------------------C
C    1.5.1                                    C
C    *** SUBROUTINE U2DREL ***                          C
C    Read and print values for a two-dimensional real array        C
C                                             C
C-----------------------------------------------------------------------C
     SUBROUTINE U2DREL(A,ANAME,II,JJ,IN,IOUT)
     DIMENSION A(jj,ii)
     CHARACTER ANAME(6)*4,FMTIN*20
C
C --- Read array control record
     READ(IN,1000) LOCAT,CNSTNT,FMTIN,IPRN
 1000 FORMAT(I10,F10.3,A20,I10)
C
```

```
C --- If LOCAT=0 then set all array values equal to CNSTNT
C --- and return
      IF(LOCAT.EQ.0) THEN
        DO 10 I=1,II
        DO 10 J=1,JJ
        A(J,I)=CNSTNT
10      continue
        WRITE(IOUT,2000) ANAME,CNSTNT
2000    FORMAT(1X,6A4,' =',G15.7)
        RETURN
C
C --- If LOCAT<>0 then read formatted records using format FMTIN
      ELSEIF(LOCAT.NE.0) THEN
        WRITE(IOUT,2010) ANAME,FMTIN
2010    FORMAT(1H1,///1X,6A4,' WILL BE READ USING FORMAT: ',
     >       A20/83('-'))
        DO 20 I=1,II
          READ(IN,FMTIN) (A(J,I),J=1,JJ)
20      CONTINUE

      ENDIF
C
C --- If LOCAT > 0, then multiply array values by CNSTNT
      IF(LOCAT.GT.0) THEN
        DO 30 I=1,II
        DO 30 J=1,JJ
        A(J,I)=A(J,I)*CNSTNT
30    CONTINUE

      ELSEIF(LOCAT.LT.0) THEN
C --- if LOCAT < 0, then subtract array values by CNSTNT
        DO 40 I=1,II
        DO 40 J=1,JJ
          A(J,I)=A(J,I)-CNSTNT
          IF(A(J,I).LT.0.) A(J,I)=0.
40      CONTINUE
      ENDIF

C --- If print code (IPRN)=>0 then print array values
      IF(IPRN.LT.0) RETURN
      CALL UPRINT(A,ANAME,0,0,JJ,II,IPRN,IOUT)
C
C --- Return
      RETURN
      END
C*************************************************************************C
C     1.5.1.1                                   C
C     *** SUBROUTINE UPRINT ***                       C
C     Print a two-dimensional array in strip form           C
C                                               C
C*************************************************************************C
      SUBROUTINE UPRINT(BUF,TEXT,KSTP,KPER,NCOL,NROW,IPRN,IOUT)
      DIMENSION BUF(100,100)
      CHARACTER TEXT(6)*4
C
C --- Make sure the format code (IPRN) is between 1 and 12
      IP=IPRN
      IF(IP.LT.1 .OR. IP.GT.12) IP=12
C
C --- Determine the number of values (NCAP) printed on one line
      IF(IP.EQ.1) NCAP=11
      IF(IP.EQ.2) NCAP=9
      IF(IP.GT.2 .AND. IP.LT.7) NCAP=15
      IF(IP.GT.6 .AND. IP.LT.12) NCAP=20
      IF(IP.EQ.12) NCAP=10
```

```
C
C --- Calculate the number of strips (NSTRIP).
      NCPF=129/NCAP
      ISP=0
      IF(NCAP.GT.12) ISP=3
      NSTRIP=(NCOL-1)/NCAP + 1
      J1=1-NCAP
      J2=0
C
C --- Loop through the strips
      DO 200 N=1,NSTRIP
C
C ---   Calculate the FIRST(J1) & the LAST(J2) columns for this strip
        J1=J1+NCAP
        J2=J2+NCAP
        IF(J2.GT.NCOL) J2=NCOL
C
C ---   Print title on each strip
        WRITE(IOUT,2000) TEXT,KSTP,KPER
 2000   FORMAT(1X,6A4,' AT END OF TIME STEP',I3,
     >      ' IN STRESS PERIOD',I3/83('-'))
C
C ---   Print column numbers above the strip
        CALL UCOLNO(J1,J2,ISP,NCAP,NCPF,IOUT)
C
C ---   Loop through the rows printing cols J1 thru J2 with format IP
        DO 100 I=1,NROW
          GO TO(1,2,3,4,5,6,7,8,9,10,11,12), IP
C
C ---     FORMAT 10G10.3
    1     WRITE(IOUT,2040) I,(BUF(J,I),J=J1,J2)
 2040       FORMAT(I4,2X,1PG10.3,10(1X,G10.3))
          GO TO 100
C
C ---     FORMAT 8G13.6
    2     WRITE(IOUT,2050) I,(BUF(J,I),J=J1,J2)
 2050       FORMAT(I4,2X,1PG13.6,8(1X,G13.6))
          GO TO 100
C
C ---     FORMAT 15F7.1
    3     WRITE(IOUT,2060) I,(BUF(J,I),J=J1,J2)
 2060       FORMAT(I4,1X,15(1X,F7.1))
          GO TO 100
C
C ---     FORMAT 15F7.2
    4     WRITE(IOUT,2070) I,(BUF(J,I),J=J1,J2)
 2070       FORMAT(I4,1X,15(1X,F7.2))
          GO TO 100
C
C ---     FORMAT 15F7.3
    5     WRITE(IOUT,2080) I,(BUF(J,I),J=J1,J2)
 2080       FORMAT(I4,1X,15(1X,F7.3))
          GO TO 100
C
C ---     FORMAT 15F7.4
    6     WRITE(IOUT,2090) I,(BUF(J,I),J=J1,J2)
 2090       FORMAT(I4,1X,15(1X,F7.4))
          GO TO 100
C
C ---     FORMAT 20F5.0
    7     WRITE(IOUT,2100) I,(BUF(J,I),J=J1,J2)
 2100       FORMAT(I4,1X,20(1X,F5.0))
          GO TO 100
C
C ---     FORMAT 20F5.1
```

```
   8     WRITE(IOUT,2110) I,(BUF(J,I),J=J1,J2)
 2110     FORMAT(I4,1X,20(1X,F5.1))
        GO TO 100
C
C ---     FORMAT 20F5.2
   9     WRITE(IOUT,2120) I,(BUF(J,I),J=J1,J2)
 2120     FORMAT(I4,1X,20(1X,F5.2))
        GO TO 100
C
C ---     FORMAT 20F5.3
  10     WRITE(IOUT,2130) I,(BUF(J,I),J=J1,J2)
 2130     FORMAT(I4,1X,20(1X,F5.3))
        GO TO 100
C
C ---     FORMAT 20F5.4
  11     WRITE(IOUT,2140) I,(BUF(J,I),J=J1,J2)
 2140     FORMAT(I4,1X,20(1X,F5.4))
        GO TO 100
C
C ---     FORMAT 9G11.4
  12     WRITE(IOUT,2150) I,(BUF(J,I),J=J1,J2)
 2150     FORMAT(I4,2X,1PG11.4,9(1X,G11.4))
C
  100   CONTINUE
  200 CONTINUE
C
C --- Return
     RETURN
     END
C*************************************************************************C
C    1.5.1.1.1                                  C
C    *** SUBROUTINE UCOLNO ***                        C
C    Print column numbers at the top of a page when arrays        C
C    are printed                                  C
C                                              C
C*************************************************************************C
     SUBROUTINE UCOLNO(NLBL1,NLBL2,NSPACE,NCPL,NDIG,IOUT)
     CHARACTER*4 BF(130),DG(10),DOT,SPACE
     DATA DG(1),DG(2),DG(3),DG(4),DG(5),DG(6),DG(7),DG(8),DG(9),DG(10)/
    >       '0  ','1  ','2  ','3  ','4  ','5  ','6  ',
    >       '7  ','8  ','9  '/
     DATA DOT,SPACE/'*  ','   '/
C
C --- Calculate # of columns to be printed (NLBL), width
C --- of a line (NTOT), number of lines (NWRAP).
     WRITE(IOUT,10)
   10 FORMAT(1X)
     NLBL=NLBL2-NLBL1+1
     N=NLBL
     IF(NLBL.GT.NCPL) N=NCPL
     NTOT=NSPACE+N*NDIG
     IF(NTOT.GT.130) GO TO 50
     NWRAP=(NLBL-1)/NCPL + 1
     J1=NLBL1-NCPL
     J2=NLBL1-1
C
C --- Build and print each line
     DO 40 N=1,NWRAP
C
C --- Clear the buffer (BF).
     DO 20 I=1,130
       BF(I)=SPACE
   20 CONTINUE
     NBF=NSPACE
C
```

```
C --- Determine first (J1) and last (J2) column # for this line
      J1=J1+NCPL
      J2=J2+NCPL
      IF(J2.GT.NLBL2) J2=NLBL2
C
C --- Load the column #'s into the buffer
      DO 30 J=J1,J2
        NBF=NBF+NDIG
        I2=J/10
        I1=J-I2*10+1
        BF(NBF)=DG(I1)
        IF(I2.EQ.0) GO TO 30
        I3=I2/10
        I2=I2-I3*10+1
        BF(NBF-1)=DG(I2)
        IF(I3.EQ.0) GO TO 30
        BF(NBF-2)=DG(I3+1)
   30 CONTINUE
C
C --- Print the contents of the buffer (i.e. print the line)
      WRITE(IOUT,31) (BF(I),I=1,NBF)
   31 FORMAT(1X,130A1)
C
   40 CONTINUE
C
C --- Print a line of dots (for esthetic purposes only)
   50 NTOT=NTOT+5
      IF(NTOT.GT.130) NTOT=130
      WRITE(IOUT,51) (DOT,I=1,NTOT)
   51 FORMAT(1X,130A1)
C
C --- Return
      RETURN
      END

C*****************************************************************************C
C    1.6                                  C
C    *** SUBROUTINE RPSBCF ***                          C
C    READ AND PREPARE DATA FOR MODULE SGFBCF                    C
C                                        C
C*****************************************************************************C
      SUBROUTINE RPSBCF (CC)
      CHARACTER ANAME(6,6)*4
$include:'com.for'
      dimension cc(Ncol,Nrow)

      DATA ANAME(1,1),ANAME(2,1),ANAME(3,1),ANAME(4,1),ANAME(5,1),
     >ANAME(6,1)/'   ','   ','   T','OP E','LEVA','TION'/
      DATA ANAME(1,2),ANAME(2,2),ANAME(3,2),ANAME(4,2),ANAME(5,2),
     >ANAME(6,2)/'   ','   ','   ','   ','   ','DELR'/
      DATA ANAME(1,3),ANAME(2,3),ANAME(3,3),ANAME(4,3),ANAME(5,3),
     >ANAME(6,3)/'   ','   ','   ','   ','   ','DELC'/
      DATA ANAME(1,4),ANAME(2,4),ANAME(3,4),ANAME(4,4),ANAME(5,4),
     >ANAME(6,4)/'   ','PRIM','ARY ','STOR','AGE ','COEF'/
      DATA ANAME(1,5),ANAME(2,5),ANAME(3,5),ANAME(4,5),ANAME(5,5),
     >ANAME(6,5)/'   H','YD. ','COND','. AL','ONG ','ROWS'/
      DATA ANAME(1,6),ANAME(2,6),ANAME(3,6),ANAME(4,6),ANAME(5,6),
     >ANAME(6,6)/'   ','   ','BOTT','OM E','LEVA','TION'/

C --- Input unit number
      IN=IUNIT(6)
C
C --- Read ratio of transmissivity in the column direction
C --- to transmissivity in the row direction (TRPY)
      READ(IN,1000) TRPY
```

```
 1000 FORMAT(F10.0)
      WRITE(79,2000) TRPY
      WRITE(IOUT,2000) TRPY
 2000 FORMAT(/,' COLUMN TO ROW ANISOTROPY =',F10.4,//)
C
C --- Read cell dimension in the row direction (DELR)
      CALL U1DREL(DELR,ANAME(1,2),NCOL,IN,IOUT)
C
C --- Read cell dimension in the column direction (DELC)
      CALL U1DREL(DELC,ANAME(1,3),NROW,IN,IOUT)
C
C --- Read specific yield of each cell at the surface layer
c     CALL U2DREL(SC1,ANAME(1,4),NROW,NCOL,IN,IOUT)
      Read (IN,1200) ISylayer
1200  Format (I10)
      Write (Iout, 1250) ISylayer
1250  Format (/,'Total soil layers with different Specific Yield, Sy:',
     >       I10)
      Do 20 I =1, ilt
      Read (IN,1300) (Sy(I,J), J=1, ISylayer)
1300  Format (4F10.3)
20    Continue

      Ic=0
      Do 25 I =1, ilt
      Ic =Ic+1
      Write (Iout, 1350) ISylayer,IC
      write (Iout, 1380) (Sy(I,J), J=1, ISylayer)
25    Continue
1350  Format(/,'Specific Yields of', I4,' layers of land use No.', I5)
1380  Format (4F10.3)

C --- Read Average hydraulic conductivity (HY) of the surface layer,
C     bottom elevation (BOT), and top elevation (TOP) for each cell
C     CALL U2DREL(HY,ANAME(1,5),NROW,NCOL,IN,IOUT)
      Read (IN, 1500) (CKS3(I), I=1, ilt)
1500  format (10F10.2)

      CALL U2DREL(BOT,ANAME(1,6),NROW,NCOL,IN,IOUT)

      write (iout,2050)
2050  format (10x,/,'Bottom Elevation of each Cell (m) '/)

      DO 21 I=1,NROW
      Write (iout, 2100) i, (bot(j,i), j=1, ncol)
   21 CONTINUE
2100  format (I5, 20F10.3)

      CALL U2DREL(TOP,ANAME(1,1),NROW,NCOL,IN,IOUT)

      write (iout,2200)
2200  format (10x,/,'Surface Elevation of each Cell (m) '/)

      DO 22 I=1,NROW

      Write (iout, 2100) i, (top(j,i), j=1, ncol)

   22 CONTINUE

C
C --- If IBOUND=0, set hydraulic conductivity (HY) equal
C --- zero, and conductance (CC) equal zero.
      Ttop=0.
      Itop=0
      DO 40 I=1,NROW
```

```
      DO 40 J=1,NCOL

        IF(IBOUND(J,I).EQ.0) THEN
          CC(J,I)=0.
        Else
        Itop=Itop+1
        Ttop=Ttop+top(j,i)
        ENDIF
   40 CONTINUE
      ATOP=Ttop/Itop

C --- RETURN
      RETURN
      END
C-------------------------------------------------------------------------------C
C    1.6.1                                    C
C    *** SUBROUTINE U1DREL ***                          C
C    Read values for a one-dimensional real array              C
C                                             C
C-------------------------------------------------------------------------------C
      SUBROUTINE U1DREL(A,ANAME,JJ,IN,IOUT)
      DIMENSION A(JJ)
      CHARACTER ANAME(6)*4,FMTIN*20
C
C --- Read array control record
      READ(IN,1000) LOCAT,CNSTNT,FMTIN,IPRN
 1000 FORMAT(I10,F10.2,A20,I10)
C
C --- Use LOCAT to see where array values come from
C
C --- If LOCAT=0 then set all array values equal to CNSTNT,
C --- and return
      IF(LOCAT.EQ.0) THEN
        DO 10 J=1,JJ
   10   A(J)=CNSTNT
        WRITE(IOUT,2000) ANAME,CNSTNT
 2000   FORMAT(1X,6A4,' =',G15.7)
        RETURN
C
C --- If LOCAT>0 then read formatted records using format FMTIN
      ELSEIF(LOCAT.GT.0) THEN
        WRITE(IOUT,2010) ANAME,LOCAT,FMTIN
 2010   FORMAT(1X,///6A4,' WILL BE READ ON UNIT',I3,
     >  ' USING FORMAT: ',A20/79('-')/)
        READ (LOCAT,FMTIN) (A(J),J=1,JJ)
      ENDIF
C
C --- If CNSTNT not zero then multiply array values by CNSTNT
      IF(CNSTNT.NE.0.) THEN
        DO 20 J=1,JJ
   20   A(J)=A(J)*CNSTNT
      ENDIF
C
C --- If print code (IPRN)=>0 then print array values
      IF(IPRN.LT.0) RETURN
      WRITE(IOUT,2020) (A(J),J=1,JJ)
 2020 FORMAT((1X,1PG12.5,9(1X,G12.5)))
      RETURN
      END
C-------------------------------------------------------------------------------C
C    1.7                                    C
C    SUBROUTINE RPSSIP ***                          C
C    Read and prepare data for module SGFSIP              C
C                                             C
C-------------------------------------------------------------------------------C
```

```
      SUBROUTINE RPSSIP

$include:'com.for'

C --- Input unit number
      IN=IUNIT(7)
C
C --- Print a message identifying SIP procedure
      WRITE(IOUT,2000) IN
 2000 FORMAT(1H1,'SIP1 --- STRONGLY IMPLICIT PROCEDURE SOLUTION',
     >    ' ADOPTED FROM MCDONALD AND HARBAUGH (1984)',/,
     >    ' INPUT READ FROM UNIT',I3//)
C
C --- Read and print maximum number of iteration (MXITER)
C --- and number of iteration parameter (NPARM)
      READ(IN,1000) MXITER,NPARM
 1000 FORMAT(2I10)
      WRITE(IOUT,2010) MXITER,NPARM
 2010 FORMAT(1X,'MAXIMUM ITERATIONS ALLOWED FOR CLOSURE =',I4,///,
     >    1X,'ITERATION PARAMETER =',I3)
C
C --- Read and print ACCL,ACLOSE,IPCALC,WSEED,IPRSIP
      READ(IN,1010) ACCL,HCLOSE,IPCALC,WSEED,IPRSIP
 1010 FORMAT(2F10.0,I10,F10.0,I10)
      IF(ACCL.EQ.0.) ACCL=1.
      WRITE(IOUT,2020)
 2020 FORMAT(///,' SOLUTION BY THE STRONGLY IMPLICIT',
     >    ' PROCEDURE',/1X,43('-'))
      WRITE(IOUT,2030) ACCL,HCLOSE,IPRSIP
 2030 FORMAT(1H ,'ACCELERATION PARAMETER =',G15.5,/,
     >    ' HEAD CHANGE CRITERION FOR CLOSURE =',E15.5/,
     >    ' SIP HEAD CHANGE PRINTOUT INTERVAL =',I9)
C
C --- Check if specified value of WSEED should be used or
C --- if seed should be calculated
      IF(IPCALC.NE.0) THEN
C
C ---   calculate seed and iteration parameters prior to
C ---   1st iteration
        WRITE(IOUT,2040)
 2040   FORMAT(' CALCULATE ITERATION PARAMETERS FROM',
     >      ' MODEL CALCULATED WSEED')
      ELSE
C
C ---   Use specified value of WSEED, calculate and print
C ---   iteration parameters
        P1=-1
        P2=NPARM-1
        DO 10 I=1,NPARM
        P1=P1+1
   10   W(I)=1.-WSEED**(P1/P2)
        WRITE(IOUT,2050) NPARM,WSEED,(W(J),J=1,NPARM)
 2050   FORMAT(1X,/,15,' ITERATION PARAMETERS CALCULATED',
     >      ' FROM SPECIFIED WSEED =',F11.8,' :'//,
     >      (10X,6E15.7))
      ENDIF
C
C --- Return
      RETURN
      END
C*************************************************************************C
C   1.8                                 C
C   *** SUBROUTINE RPSSOR ***                       C
C   Read and prepare data for module SGFSOR          C
C                                       C
```

```
C*******************************************************************C
      SUBROUTINE RPSSOR

$include:'com.for'

C --- Input unit number
      IN=IUNIT(8)
C
C --- Print a message identify SOR procedure
      WRITE(IOUT,2000) IN
 2000 FORMAT(1H1,/'SOR1 --- SLICE-SUCCESSIVE OVERRELAXATION',
     >    ' PROCEDURE ADOPTED FROM MCDONALD AND HARBAUGH',
     >    ' (1984)',/,' INPUT READ FROM UNIT',I3)
C
C --- Read and print maximum number of iteration (MXITER)
      READ(IN,1000) MXITER
 1000 FORMAT(I10)
      WRITE(IOUT,2010) MXITER
 2010 FORMAT(1X,'MAXIMUM ITERATIONS ALLOWED FOR CLOSURE =',I5)
C
C --- Read the acceleration parameters/relaxation factor (ACCL),
C --- the closure criterion (HCLOSE) and the number of time
C --- steps between printouts of maximum head changes (IPRSOR)
      READ(IN,1010) ACCL,HCLOSE,IPRSOR
 1010 FORMAT(2F10.0,I10)
      IF(ACCL.EQ.0.) ACCL=1.
      IF(IPRSOR.LT.1) IPRSOR=999
C
C --- Print ACCL,HCLOSE,IPRSOR
      WRITE(IOUT,2020) ACCL,HCLOSE,IPRSOR
 2020 FORMAT(/,' ACCELERATION PARAMETER =',G15.5,/,
     >    ' HEAD CHANGE CRITERION FOR CLOSURE =',E15.5,/,
     >    ' SOR HEAD CHANGE PRINTOUT INTERVAL =',I9)
C
C --- Return
      RETURN
      END


$NOFLOATCALLS
$STORAGE:2
$debug
C*******************************************************************C
C   2.0                                C
C   *** SUBROUTINE COAATM ***                          C
C   Input daily precipitation, daily temperature, and calculate    C
C   daily potential evapotranspiration by using Hamon's equation.  C
C                                      C
C*******************************************************************C
      SUBROUTINE COAATM(IBDAY,ICY)
      integer print,JJday,YY

$include:'com.for'

      DIMENSION MONTHD(12),MONTHL(12),TEMP(366),STAX(5),STAY(5)

C --- WRITE TITLE TO FILES

      WRITE(79,2000)
 2000   FORMAT(/'YEAR JDAY  MON DAY PREC INTCEP',
     >      ' PET EVPT  AE   AT  UZ1  UZ2',
     >' UZ3',' UDRAIN',' HEAD  GFlow RivFlow TFlow  Leakage')
      WRITE(90,2005)
2005   Format('MonYear ','Data',1x,'MFlow(mm)',2x,'SFlow', 1x,'SddFlow',
     > 2x,'R1  ', 2x,'Mwt  ', 2x,'Swt', 6x, 'Sddwt  ', 2x, 'R2  ')
```

```
      WRITE(80,2008)
 2008   Format ('MonYear ','Icount', 1x,'STFlow',
     >  1x,'SHead', 2x,' Rain', 3x,'AET', 3x, 'Inter', 2x, 'Udrain',2x,
     >  'Gflow',2x,'Sevpt',3x,'SAE',3x,'SAT',4x,'Sleak')

C --- Number of days for each month during regular year
      DATA MONTHD/31,28,31,30,31,30,31,31,30,31,30,31/
C
C --- Number of days for each month during leap year
      DATA MONTHL/31,29,31,30,31,30,31,31,30,31,30,31/
      INATM=IUNIT(10)
      INreal= IUNIT(11)
C
C --- Read year, ending month (ILM), starting Julian day (IBDAY),
C --- a flag (IFLAG=1, measured stream flow were read in),
C --- and number of raingages (NSTA)
      READ(INATM,1000) YEAR,ILM,IBDAY,IFLAG,NSTA
 1000 FORMAT(5I10)
C
C --- Read row and column coordinate (STAX and STAY) of each
C --- weather station and calculate distanace between active
C --- cell and each weather station and saved in DIST array
      DO 5 I=1,NSTA
        READ(INATM,1005) STAX(I),STAY(I)
 1005   FORMAT(2F10.0)
        DO 7 J=1,Ncell
          ROW=LADUSE(J,5)
          COL=LADUSE(J,6)
          DIST(J,I)=SQRT((ROW-STAX(I))**2+(COL-STAY(I))**2)
    7   CONTINUE
    5 CONTINUE
C
C --- Look for leap year
      NDAY = 365
      IF(YEAR/4*4.NE.YEAR) GO TO 10
      IF(YEAR/400*400.EQ.YEAR) GO TO 10
      NDAY=366
   10 CONTINUE
C
C --- Decide number of days for each month according to year
      IF(NDAY.EQ.365) THEN
        DO 20 I=1,12
   20   MDAY(I)=MONTHD(I)
      ELSE
        DO 30 I=1,12
   30   MDAY(I)=MONTHL(I)
      ENDIF
      DO 25 J=1,NSTA
C
C ---   Read and print daily precipitation
        READ(INATM,1010)(YY,IMM,IID,JJday,PRECIP(I),temp(i),I=1,NDAY)
 1010   FORMAT(4I8, F8.2, F10.2)
        DO 35 I=1,NDAY
        RAIN(I,J)=PRECIP(I)*25.4
   35   PRECIP(I)=PRECIP(I)*25.4
        WRITE(IOUT,2010) YEAR,J
 2010   FORMAT(1H1,/,' DAILY PRECIPITATION FOR YEAR ',I4,' (mm)'/,
     >         ' RAINGAGE STATION # ',I2)
        index=1
        CALL ATMDP1(PRECIP,NDAY,MDAY,IOUT,index)
   25   CONTINUE
C
C ---   Print daily temperature

      WRITE(IOUT,2020) YEAR
```

```
 2020 FORMAT('DAILY MEAN TEMPERATURE FOR YEAR ',I4,' (CELSIUS)'/)
      index = 0
      CALL ATMDP1(TEMP,NDAY,MDAY,IOUT, index)
C
C --- Calculate daily potential evapotranspiration
      ICOUNT=0
      DO 50 I=1,12
        DO 40 J=1,MDAY(I)
          ICOUNT=ICOUNT+1
          DTEMP=TEMP(ICOUNT)
          CALL ATMPE(DTEMP,I,J,DEGLAT,PEC,DPE)
          PET(ICOUNT)=DPE
   40   CONTINUE
   50 CONTINUE
C
C --- Print daily potential evapotranspiration

      WRITE(IOUT,2030) YEAR,DEGLAT,PEC
 2030 FORMAT(/,'CALCULATED DAILY POTENTIAL EVAPOTRANSPIRATION FOR YEAR
     >',I4,' (mm)'//' LATITUDE =',F7.2/' PE CORRECTION FACTOR ='F5.2//)
C
      CALL ATMDP1(PET,NDAY,MDAY,IOUT,1)
C
C --- Initialize REFLOW
      DO 65 I=1,366

   65 REFLOW(I)=0.
C
C --- Read and print measured daily stream discharge if IFLAG=1
      IF(IUNIT(11) .NE. 0) THEN
      read (inreal,2035) indexrun, indexwt
      write (iout, 2036) indexrun, indexwt
2035  format (2I10)
2036  format ('Index for measured data, runoff (mm/day) and
     >water table elevation (m)',/, 2I10)

      Do 55 I = Ibday, Nday
        READ(INreal,1020) YY,IMM,IID,JJday,MID(i),REflow(I),MWT(i)
        write (iout, 1020) YY,IMM,IID,JJday,MID(i),REflow(I),MWT(i)
 1020   FORMAT(5I8, F8.1, F8.3)
   55 Continue

        WRITE(IOUT,2050) YEAR
 2050   FORMAT(1H1,' MEASURED DAILY STREAMFLOW FOR YEAR ',I4,
     >        ' (mm)'//)
        CALL ATMDP1(REFLOW,NDAY,MDAY,IOUT,1)

c       WRITE(IOUT,2050) YEAR
c 2050   FORMAT(1H1,' MEASURED DAILY WaterTable FOR YEAR ',I4,
c    >        ' (m)'//)
c       CALL ATMDP1(REFLOW,NDAY,MDAY,IOUT,0)


      ENDIF
C
C --- Calculate LAI for each day

      CALL ATMSEA(NDAY,icy)
      print=0
      write (iout,2060) YEAR
 2060 FORMAT(//'LAI of simulated Forest for year',I4//)

      CALL ATMDP2(LAI,NDAY,print)

      WRITE(IOUT,2070) YEAR
```

```
 2070 FORMAT(//'LAI of Mature Forest for year',I4//)

      CALL ATMDP2(MLAI,NDAY,print)

C
C --- Return
      RETURN
      END
C*************************************************************************C
C   2.1                                  C
C   *** SUBROUTINE ATMPE ***                          C
C   Calculate potential evapotranspiration by using Hamon's       C
C   equation                                C
C                                        C
C*************************************************************************C
      SUBROUTINE ATMPE(TEMP,MONTH,J,DEGLAT,PEC,PE)
      Double precision  cwt
C --- Determine daylength from latitude and date
      ANL = J
      GO TO (1,2,3,4,5,6,7,8,9,10,11,12),MONTH
    1 ANO = 50.+31.-ANL
      ANO = -ANO
      GO TO 13
    2 ANO = 22.+28.-ANL
      ANO = -ANO
      GO TO 13
    3 ANO = ANL-22.
      GO TO 13
    4 ANO = 9.+ANL
      GO TO 13
    5 ANO = 39.+ANL
      GO TO 13
    6 ANO = 70.+ANL
      GO TO 13
    7 ANO = 31.-ANL+53.
      GO TO 13
    8 ANO = 22.+31.-ANL
      GO TO 13
    9 ANO = 22.-ANL
      GO TO 13
   10 ANO = 8.+ANL
      ANO = -ANO
      GO TO 13
   11 ANO = 39.0+ANL
      ANO = -ANO
      GO TO 13
   12 ANO = 69.+ANL
      ANO = -ANO
   13 D = .0174529*23.5*SIN(ANO*.0174529)
      ALTIT = DEGLAT*.0174529
      IF(D) 14,16,15
   14 CWT = -SIN(D)/COS(D)*(SIN(ALTIT)/COS(ALTIT))
      TWT = SQRT(1.-CWT**2)/CWT
      T = ATAN(TWT)/.2618
      GO TO 17
   15 CWT = -SIN(D)/COS(D)*(SIN(ALTIT)/COS(ALTIT))
      TWT = SQRT(1.-CWT**2)/CWT
      T = (3.1416+ATAN(TWT))/.26175
      GO TO 17
   16 T = 6.
   17 DAY = 2.0*T/12.0
      T = T*2.0
C
C --- Calculate PE
C --- ESAT = saturated vapor pressure at TEMP
```

```
C --- TEMP = mean daily temperature at celces
C --- RHOSAT = saturated vapor density at TEMP
      ESAT = 6.108*EXP(17.2693882*TEMP/(TEMP+237.3))
      RHOSAT = 216.7*ESAT/(TEMP+273.3)
      PE = PEC*0.1651*DAY*RHOSAT
      RETURN
      END
C*************************************************************************C
C   2.2.1                                   C
C   *** SUBROUTINE ATMDP ***                        C
C   Utility subroutine to print out daily values by months.      C
C   Monthly and annual totals are also calculated.          C
C                                           C
C*************************************************************************C
      SUBROUTINE ATMDP1(VALUE,NDAY,MDAY,IOUT,INDEX)
      DIMENSION VALUE(366),TOTAL(12),MDAY(12)
C
C ---  +++ WRITE FORMAT +++
2000  FORMAT('0',1X,'DAY',6X,'JAN.',6X,'FEB.',6X,'MAR.',6X,'APR.',7X,'MA
     >Y',6X,'JUNE',6X,'JULY',6X,'AUG.',5X,'SEPT.',6X,'OCT.',6X,'NOV.',6X
     >,'DEC.',2X,'DAY'/)
2010  FORMAT(I4,1X,12F10.2,I4)
2020  FORMAT(I4,1X,F10.2,10X,10F10.2,I4)
2030  FORMAT(I4,1X,3(F10.2,10X),2F10.2,2(10X,F10.2),I4)
2040  FORMAT(///1X,'TOTAL',12F10.2///10X,'TOTAL FOR WATER YEAR =',
     >      F10.2,' mm'/)
C
C --- Initialization
      ANNUAL = 0.0
      DO 10 I=1,12
   10 TOTAL(I)=0.0
      L=0
      IF(NDAY.EQ.366) L=1
C
C --- Print title
      WRITE(IOUT,2000)
C
C --- Print daily values
      DO 20 N=1,28
      WRITE(IOUT,2010)N,VALUE(N),VALUE(31+N),VALUE(59+N+L),VALUE(90+N+L)
     >,VALUE(120+N+L),VALUE(151+N+L),VALUE(181+N+L),VALUE(212+N+L),
     >VALUE(242+N+L),VALUE(273+N+L),VALUE(303+N+L),VALUE(334+N+L),N
   20 CONTINUE
      N=29
      IF(L.EQ.0) THEN
        WRITE(IOUT,2020) N,VALUE(N+L),VALUE(59+N+L),VALUE(90+N+L),
     >   VALUE(120+N+L),VALUE(151+N+L),VALUE(181+N+L),
     >   VALUE(212+N+L),VALUE(242+N+L),VALUE(273+N+L),
     >   VALUE(303+N+L),VALUE(334+N+L),N
      ELSE
       WRITE(IOUT,2010) N,VALUE(N),VALUE(31+N),VALUE(59+N+L),
     >VALUE(90+N+L),VALUE(120+N+L),VALUE(151+N+L),
     >VALUE(181+N+L),VALUE(212+N+L),VALUE(242+N+L),
     >VALUE(273+N+L),VALUE(303+N+L),VALUE(334+N+L),N
      ENDIF
      N=30
        WRITE(IOUT,2020) N,VALUE(N+L),VALUE(59+N+L),
     >VALUE(90+N+L),VALUE(120+N+L),VALUE(151+N+L),VALUE(181+N+L)
     >,VALUE(212+N+L),VALUE(242+N+L),VALUE(273+N+L),
     > VALUE(303+N+L),VALUE(334+N+L),N
      N=31
      WRITE(IOUT,2030) N,VALUE(N),VALUE(59+N+L),VALUE(120+N+L),
     >VALUE(181+N+L),VALUE(212+N+L),VALUE(273+N+L),
     >VALUE(334+N+L),N
```

```
100  Continue


     IF(INDEX.EQ.1) THEN
C ---   Calculate monthly and annual total
        M=0
        DO 30 I=1,12
        DO 40 J=1,MDAY(I)
           M=M+1
  40     TOTAL(I)= TOTAL(I)+VALUE(M)
        ANNUAL=ANNUAL+TOTAL(I)
  30    CONTINUE
C ---   print monthly and annual total
        WRITE(IOUT,2040) (TOTAL(M),M=1,12),ANNUAL
     ENDIF

     RETURN
     END
C*************************************************************************C
C    2.2.2                                    C
C    *** SUBROUTINE ATMDP ***                      C
C    Utility subroutine to print out daily values by months.      C
C    Monthly and annual totals are also calculated.            C
C                                             C
C*************************************************************************C
     SUBROUTINE ATMDP2(VALUE,NDAY,INDEX)
$include:'com.for'

     DIMENSION VALUE(5,10000),TOTAL(12)
C
C ---   +++ WRITE FORMAT +++
2000  FORMAT('0',1X,'DAY',6X,'JAN.',6X,'FEB.',6X,'MAR.',6X,'APR.',7X,'MA
    >Y',6X,'JUNE',6X,'JULY',6X,'AUG.',5X,'SEPT.',6X,'OCT.',6X,'NOV.',6X
    >,'DEC.',2X,'DAY'/)
2010  FORMAT(I4,1X,12F10.2,I4)
2020  FORMAT(I4,1X,F10.2,10X,10F10.2,I4)
2030  FORMAT(I4,1X,3(F10.2,10X),2F10.2,2(10X,F10.2),I4)
2040  FORMAT(///1X,'TOTAL',12F10.2///10X,'TOTAL FOR WATER YEAR =',
    >      F10.2,' mm'/)
C
C --- Initialization
     ANNUAL = 0.0

     DO 10 I=1,12
   10 TOTAL(I)=0.0
     L=0
     IF(NDAY.EQ.366) L=1

     Do 100 I=1,ilt

     write (iout, 2050)  I

2050  format (/'LAND USE', 15,/)
C
C --- Print title
     WRITE(iout,2000)

C --- Print daily values
     DO 20 N=1,28
     WRITE(IOUT,2010) N,VALUE(i,N),VALUE(i,31+N),VALUE(i,59+N+L),
    > VALUE(i,90+N+L)
    >,VALUE(i,120+N+L),VALUE(i,151+N+L),VALUE(i,181+N+L),
    >VALUE(i,212+N+L),
    >VALUE(i,242+N+L),VALUE(i,273+N+L),VALUE(i,303+N+L),
    >VALUE(i,334+N+L),N
```

```
   20 CONTINUE
     N=29
     IF(L.EQ.0) THEN
       WRITE(IOUT,2020) N,VALUE(i,N+L),VALUE(i,59+N+L),VALUE(i,90+N+L)
    >   ,
    >  VALUE(i,120+N+L),VALUE(i,151+N+L),VALUE(i,181+N+L),
    >  VALUE(i,212+N+L),VALUE(i,242+N+L),VALUE(i,273+N+L),
    >  VALUE(i,303+N+L),VALUE(i,334+N+L),N
     ELSE
      WRITE(IOUT,2010) N,VALUE(i,N),VALUE(i,31+N),VALUE(i,59+N+L),
    >VALUE(i,90+N+L),VALUE(i,120+N+L),VALUE(i,151+N+L),
    >VALUE(i,181+N+L),VALUE(i,212+N+L),VALUE(i,242+N+L),
    >VALUE(i,273+N+L),VALUE(i,303+N+L),VALUE(i,334+N+L),N
     ENDIF
     N=30
       WRITE(IOUT,2020) N,VALUE(i,N+L),VALUE(i,59+N+L),
    >VALUE(i,90+N+L),VALUE(i,120+N+L),VALUE(i,151+N+L),VALUE(i,181+N+L)
    >,VALUE(i,212+N+L),VALUE(i,242+N+L),VALUE(i,273+N+L),
    > VALUE(i,303+N+L),VALUE(i,334+N+L),N
     N=31
     WRITE(IOUT,2030) N,VALUE(i,N),VALUE(i,59+N+L),VALUE(i,120+N+L),
    >VALUE(i,181+N+L),VALUE(i,212+N+L),VALUE(i,273+N+L),
    >VALUE(i,334+N+L),N


     IF(INDEX.EQ.1) THEN
C ---   Calculate monthly and annual total

       M=0
       DO 30 Ik=1,12
       DO 40 J=1,MDAY(IK)
          M=M+1
  40     TOTAL(Ik)= TOTAL(Ik)+VALUE(i,M)
        ANNUAL=ANNUAL+TOTAL(Ik)
  30   CONTINUE
C ---   print monthly and annual total

  70   continue
       WRITE(IOUT,2040) (TOTAL(M),M=1,12),ANNUAL

     ENDIF
 100  continue

     RETURN
     END

C*************************************************************************C
C    2.3                                  C
C    *** SUBROUTINE ATMSEA ***                        C
C    Subroutine to set up season function to calculate phenologic    C
C    index LAI for each day                          C
C                                         C
C*************************************************************************C
     SUBROUTINE ATMSEA(NDAY,icy)

$include:'com.for'

C --- Calculate Leaf Area Index for the year

     DO 60 I = I, ILT
       IF(CLAI(I) .GE. 1.) GO TO 60
     IF (ICY .LT. 2) THEN
     CLAI(I) = 0.1
     ELSE IF (ICY .GT. 15) THEN
```

```
      CLAI(I) = 1.

      ELSE
      CLAI(I)= (ICY-1.5)/(ICY+0.01)
      ENDIF

   60 CONTINUE

      Do 100 I=1,ilt
      Do 100 j=1, NDAY

C .... if the landuse is cypress wetlands, calculate LAI by a piecewise linear
C ..... equation and assume they are in mature states

      if (I .eq.1) then
         if ( j .le. 61) then
            LAI(i,j)=1.2*CLAI(i)
         elseif (j  .gt. 121) then
           LAI(i,j) = CLAI(i)*(1.5 + 4.4*sin(1.1*3.14159*Float(J)
     >       /365.+1.9*3.14159))
         else
           LAI(i,j)= CLAI(i)*(1.2+(3.93-1.2)/(121.-61.)*Float(j-61))
         Endif

      Else
C ... calcualte daily LAI for pine forests by a sin function

      LAI(I,J) = CLAI(i)*(5.0 + 0.90 * Sin((2.0*3.141592/365.*Float(J)+
     >       2.0*3.14159/2.0)*0.92))
      Endif

C ... calcualte the daily LAI for mature wetlands
      if (I .eq.1) then
         if ( j .le. 61) then
            MLAI(i,j)=1.2
         elseif (j  .gt. 121) then
            MLAI(i,j) = (1.5 + 4.4*sin(1.1*3.14159*Float(J)
     >       /365.+1.9*3.14159))
         else
            MLAI(i,j) = 1.2 +(3.93-1.2)/(121.-61.) *Float(j-61)
         Endif

      Else
C .... for mature pine forests

      MLAI(I,J) =(5.0 + 0.90 * Sin((2.0*3.141592/365.*Float(J)+
     >       2.0*3.14159/2.0)*0.92))

      Endif

  100 Continue

      RETURN

      END


C*************************************************************************C
C   3.0                                C
C   *** SUBROUTINE COAINT ***                      C
C   Simulate daily rainfall interception              C
C                                C
C*************************************************************************C
      SUBROUTINE COAINT(IDAY)
      Real Cypress, Pine
```

```
$include:'com.for'

C
C --- Initialize PINT array
      DO 10 I=1, Ncell
   10 PINT(I)=0.
C
C --- Calculate rainfall interception for each active cell
      DO 20 I=1,Ncell
C
C ---   Calculate daily precipitaion (mm) for each cell according
C ---   to distance to each weather stations
        AA=0.
        BB=0.

         DO 15 II=1,NSTA
          if (dist(I,II) .ne. 0) then
          AA=AA+RAIN(IDAY,II)/DIST(I,II)
          BB=BB+1./DIST(I,II)

        PRECIP(I)=AA/BB
        else
        precip (i) = rain(Iday,II)
       endif
15      continue

C
C ---   Assign landuse information
        Cypress = LADUSE(I,2)*0.01
        PINE    = LADUSE(I,1)*0.01
C
C ---   Calculate maximum daily rainfall interception (mm)

        PMXINT = Cypress*LAI(1,Iday)*1. + Pine*LAI(2,iday)*1. + 1.12*1.

C ---   Calculate daily rainfall interception (mm) (modified by GS)

        if ( lid(i) .eq. 2)  then
        SSinter=.085*precip(i)
        else
        SSinter =0.07*precip(i)
        endif

        PINT(I) = Cypress*(0.02+0.15*PRECIP(I))+
     >          Pine*(0.02+0.134*PRECIP(I)) + SSinter

       IF(PINT(I).GT.PMXINT) PINT(I)=PMXINT
       IF(PINT(I).GT.PRECIP(I)) PINT(I)=PRECIP(I)

C ---   Calculate remaining interception storage(mm)(DEFINT)
        DEFINT = PMXINT-SINT(I)
        IF(DEFINT.LT.0.) DEFINT=0.
        IF(PINT(I).GT.DEFINT) PINT(I)=DEFINT
C ---   Assign precipitation interception to interception storage
C ---   reservior (mm)(SINT)
        SINT(I)=SINT(I)+PINT(I)
   20 CONTINUE
C
C --- Return
      RETURN
      END


$NOFLOATCALLS
```

```
$STORAGE:2
$DEBUG
C*************************************************************************C
C   4.0                                C
C   *** SUBROUTINE COAUSF ***                          C
C   Simulate water flow within the unsatureated zone.          C
C   Moisture content and moisture drain from the              C
C   unsaturated zone into the saturated ground water          C
C   zone are calculated.                          C
C                                          C
C   THIS SUBROUTINE IS MODIFIED BY Ge Sun, UF, 1995            C
C   New features added:                          C
C   1. intitial soil moisture content is a function of initital    C
C      water tabel level. This function depends on landuse types.  C
C   2. Drainage rate is modeled by Van Genuchen Type Equations.    C
C     K(theta) = f(theta) if SMC<field capacity, K=0 cm/day       C
C                                          C
C   3. UUZONE = water stored in the unsaturated zone, if the soil is C
C      saturted, it equals to zero. UZONE = cm water stored in the
C      entire layer ( there are three layers used)
C   4. Variables used:
C   ATH = aquifer thickness (cm) = top -bottom -unsaturated depth
C
C*************************************************************************C
    SUBROUTINE COAUSF(IDAY,HNEW,HOLD,ibday,ICY,uzone1,uzone2,uzone3)

    REAL INFIL

$include:'com.for'

    dimension uzone1(Ncell),uzone2(Ncell),uzone3(Ncell)

    dimension INFIL(200),HNEW(ncol,nrow),HOLD(ncol,nrow)

C --- Initialize unsaturated zone drainage rate

    DO 10 I=1,Ncell
      UDRAIN(I)=0.
c       WFLOW(I)=0.
C ---   Calculate daily infiltration
      IF(PRECIP(I).EQ.0.) THEN
        INFIL(I)=0.
      ELSE
        INFIL(I)=PRECIP(I)-PINT(I)
      ENDIF
  10 CONTINUE

C.....print the title  of the file that contains intial soil moisture content
C..... in BASIC.OUT

    if (iday .eq. ibday .and. ICY .eq. 1) then
      write (iout, 15)
15     format (/,15x,'Initial Soil Moisture Content of the Three Layer
   >'//, 'Iday Cell  Depth     SMC1     SMC2     SMC3  ',
   >'UUZONE1   UUZONE2  UUZONE3  UZONE1  UZONE2  UZONE3')
    endif

    ICell=0
    DO 100 I=1,NROW
    DO 100 J=1,NCOL

      IF(IBOUND(J,I).EQ.0) GO TO 100
      ICell=ICell+1
      id =iid(icell)
c
```

```
C ---   Calculate unsaturated zone depth in cm

      Dep =  (TOP(J,I)-Hnew(J,I))*100.

      UDEPTH=DEP
      OUDEP=(TOP(J,I)-HOLD(J,I))*100.
C ---   Calculate aquifer thickness in cm
      ath=(top(j,i)-bot(j,i))*100.
      ath=ath-dep
C ---   Decide number of layers of the unsaturated zone
      IF(DEP.GE.65.0) LAYER=3
      IF(DEP.LT.65.0) LAYER=2
      IF(DEP.LT.40.0) LAYER=1
      IF(DEP.LE. 0.0) LAYER=0

C.... If this is the first day of simulation, intial soil moisture content for
C.... the three layers are initialized by an empirical function related to initial
C.... water table depth.

    If (iday .eq. ibday .and. ICY .eq. 1) then

       if (layer .eq. 3) then

       if (dep .ge. 75.0) then

      SMC3(icell)=(ssmc(id,3)-rsmc(id,3))*(1+(wa(id,3)*
     >  (dep-75.0))**wb(id,3)) **(wc(id,3))+rsmc(id,3)

      else
         smc3(icell)=fc(id,3)
      end if

      SMC2(icell)=(ssmc(id,2)-rsmc(id,2))*( 1+(wa(id,2)*
     >          (dep-45.0))**wb(id,2))**wc(id,2)+rsmc(id,2)

      SMC1(icell)=(ssmc(id,1)-rsmc(id,1))*( 1+(wa(id,1)*
     >          (dep-20.0))**wb(id,1))**wc(id,1)+rsmc(id,1)

       uuzone1(icell)=smc1(icell)*40.
       uzone1(icell) = uuzone1(icell)

       uuzone2(icell)=smc2(icell)*25.
       uzone2(icell)=uuzone2(icell)

       uuzone3(icell)=smc3(icell)*(dep-65.)
       uzone3(icell)=uuzone3(icell)+ssmc(id,3)*ath

    else if (layer .eq. 2 ) then

       if (dep .ge. 55.0) then
          SMC2(icell)=(ssmc(id,2)-rsmc(id,2)) * ( 1+(wa(id,2)*
     >       (dep-55.0))**wb(id,2))**wc(id,2)+rsmc(id,2)
       else
          smc2(icell)=fc(id,2)
       end if

       smc1(icell)=(ssmc(id,1)-rsmc(id,1))*(1+(wa(id,1)*
     >       (dep-20.0))**wb(id,1))**wc(id,1)+rsmc(id,1)

      uuzone1(icell)= smc1(icell)*40.
      uzone1(icell)=uuzone1(icell)

      uuzone2(icell)= smc2(icell)*(dep-25.)
      uzone2(icell)=uuzone2(icell)+ssmc(id,2)*(65.-dep)
```

```
          smc3(icell)=ssmc(id,3)
          uuzone3(icell)= 0.
          uzone3(icell)= uuzone3(icell)+smc3(icell)*(Ath+dep-65.)

C -----     only one layer
         elseif  (layer .eq. 1) then

          if (dep .ge. 20.0) then
              smc1(icell) = fc(id,1)
          else
              smc1(icell)=fc(id,1)
          end if

          uuzone1(icell)=smc1(icell)*dep
          uzone1(icell)=ssmc(id,1)*(40.- dep)+uuzone1(icell)

          smc2(icell) =ssmc(id,2)
          uuzone2(icell) =0.
          uzone2(icell)=uuzone2(icell)+smc2(icell)*25.0

          smc3(icell) =ssmc(id,3)
          uuzone3(icell)=0.
          uzone3(icell)= uuzone3(icell)+smc3(icell)*(ath+dep-65.)

C ------ if water table is above soil surface,layer =0.
         else

         smc1(icell) = ssmc(id,1)
         uuzone1(icell) = 0.
         uzone1(icell)  = smc1 (icell)*40.
         smc2(icell) = ssmc(id,2)
         uuzone2(icell) = 0.
         uzone2(icell) = smc2(icell)*25.
         smc3(icell) = ssmc(id,3)
         uuzone3(icell) = 0.
         uzone3(icell) = smc3(icell)*( top(j,i)-bot(j,i)-0.65)*100.00

        end if

C ----- write initial soil moisture infromation to the BASIC.out file

        write(iout,25) iday,icell,dep,smc1(icell),smc2(icell),
    >    smc3(icell),uuzone1(icell), uuzone2(icell),uuzone3(icell),
    >    uzone1(icell),uzone2(icell),uzone3(icell)
25       format (2I4, 10F10.2)

C    today of the simulation is not the first day. soil moisture content
C    must be updated since flutuations of WT affact water content in the
C    of the zone affacted.

     Else

C      if this is not the first day of simulation,
C ---  Calculate new soil moisture contents by soil water balance methdod
C      (added by Ge Sun)
C ---  If ground water level decreased and layer numbers increased
      IF(LAYER.GT.PLAYER(ICell)) THEN
        IF(LAYER.EQ.3) THEN
C ---    if water table drops from layer 2 to layer 3
          if (player(icell) .eq. 2 ) then

          uUZONE2(ICell)=uUZONE2(ICell)+ fc(id,2)*(65.- OUDEP)
          smc2(icell) = uuzone2(icell)/25.
          Uzone2(icell)=uuzone2(icell)
```

```
          uuzone3(ICell)= fc(id,3)*(dep-65.)
          smc3(icell) = uuzone3(icell)/(dep-65.)
          uzone3(icell)=uuzone3(icell)+ssmc(id,3)*ath

C ---     if the water table drops from layer 1 to layer 3
          else if (player(icell) .eq.1) then

          uuzone1(icell)=uuzone1(icell)+ fc(id,1)*(40.-oudep)
          uzone1(icell)=uuzone1(icell)
          smc1(icell)=uzone1(icell)/40.

          uuzone2(ICell)=fc(id,2)*25.
          Uzone2(icell)=uuzone2(icell)
          smc2(icell)=fc(id,2)

          uuzone3(ICell)= fc(id,3)*(dep-65.)
          uzone3(icell)=uuzone3(icell) + ssmc(id,3)*ath
          smc3(icell)=fc(id,3)

          endif

C ----    if the water table drops from 1 to 2

        ELSEIF(LAYER.EQ.2) THEN
          uUZONE1(ICell)=uUZONE1(ICell) + fc(id,1)*(40.- OUDEP)
          uzone1(icell) = uuzone1(icell)
          smc1(icell) = uzone1(icell)/40.

          uUZONE2(ICell) = fc(id,2)*(DEP-40.)
          uzone2(icell) = uuzone2(icell) + ssmc(id,2)*(65.-dep)
          smc2(icell) = fc(id,2)

          uuzone3(icell)=0.
          uzone3(icell)=ssmc(id,3)*(ath+dep-65.)
          smc3(icell)=ssmc(id,3)

C ----    if the water table drops from 0 to 1

        ELSEIF(LAYER.EQ.1) THEN

          uUZONE1(ICell)=fc(id,1)*dep
          uzone1(icell)=uuzone1(icell)+ssmc(id,1)*(40.-dep)
          smc1(icell) = fc(id,1)

          uuzone2(icell)=0.
          uzone2(icell) = ssmc(id,2)*25.
          smc2(icell) = ssmc(id,2)

          uuzone3(icell)=0.
          uzone3(icell)=ssmc(id,3)*(ath+dep-65.)
          smc3(icell)=ssmc(id,3)

          ENDIF

C ---   If ground water level increased and layer numbers decreased
        ELSEIF(LAYER.LT.PLAYER(lCell)) THEN

C ---   water table rises from layer 3 to layer2
        IF(LAYER.EQ.2) THEN

          Uzone3(icell) = ssmc(id,3)*(ath+dep-65.)
          uuzone3(icell)=0.
          uUZONE2(ICell) = smc2(lCell)*(dep-40.)
          uzone2(icell)=uuzone2(icell)+ssmc(id,2)*(65.-dep)
```

```
      ELSEIF(LAYER.EQ.1) THEN
C ---  water table rise from layer 3 or 2 to layer 1

        uuzone3(icell) = 0.
        smc3(icell) = ssmc(id,3)
        Uzone3(icell)  = smc3(icell)*(ath+dep-65.)

        uuzone2(icell) = 0.
        smc2(icell)    = ssmc(id,2)
        uzone2(icell)  = smc2(icell)*25.

        uuZONE1(ICell) = smc1(icell)*dep
        uzone1(icell)  = uuzone1(icell) +ssmc(id,1)*(40.-dep)

      ELSE
C ---  water table rise from layer 3, 2 or layer 1 to layer 0

        uuzone3(icell) = 0.
        smc3(icell) = ssmc(id,3)
        Uzone3(icell)= smc3(icell)*((TOP(j,i)-BOT(j,i))*100.-65.)

        uuzone2(icell) = 0.
        smc2(icell)    = ssmc(id,2)
        uzone2(icell)  = smc2(icell)*25.

        uuZONE1(ICell) = 0.
        smc1(icell)    = ssmc(id,1)
        uzone1(icell)  = smc1(icell)*40.

      Endif

C ---  If the number of unsaturated zone layers did not changed
      ELSEIF(LAYER.EQ.PLAYER(ICell)) THEN

       DEPCH=(HOLD(J,I)-HNEW(J,I))*100.

       if (layer .eq. 3) then
C ....  if water tables rise
         if (depch .lt. 0.) then
         uuzone3(ICell) = smc3(icell)*(dep-65.)
         else
         uuzone3(ICell) = uuzone3(icell)+fc(id,3)*depch
         smc3(icell) = uuzone3(icell)/(dep-65.)
         endif
         uzone3(icell)  = uuzone3(icell) + ssmc(id,3)*ath

       else if (LAYER.EQ.2) THEN
         if (depch .lt. 0.) then
         uuzone2(ICell) = smc2(icell)*(dep-40.)
         else
         uuzone2(ICell) = uuzone2(icell)+fc(id,2)*depch
         smc2(icell) = uuzone2(icell)/(dep-40.)
         endif
         uzone2(icell)=uuzone2(icell) + ssmc(id,2)*(65.-dep)

       ELSE if (LAYER.EQ.1) THEN
       if (depch .lt. 0.) then
         uuzone1(ICell) = smc1(icell)*dep
         else
         uuzone1(ICell) = uuzone1(icell)+fc(id,1)*depch
         smc1(icell) = uuzone1(icell)/dep
         endif
         uzone1(icell) = uuzone1(icell)+ ssmc(id,1)*(40.-dep)

       ENDIF
```

```
      ENDIF

     Endif

C --- Unsaturated zone water flow simulation starting from the first day.

C .... if unsaturated layer equals 0, change the unit of infil from mm/day to cm/day
C .... no change to soil moisture content; recharge = net rainfall or infil.
     If (layer .eq. 0) then

     Udrain(icell) = infil(icell)*0.10

C .... if unsaturated layer equals 1, change the unit of infil from mm/day to cm/day

     ELSE IF(LAYER.EQ.1) THEN

       udrain1=0.

c..... determine how many interation is requied
       If(infil(icell) .lt. 1. .AND. smc1(icell) .lt. rsmc(id,1))then
       NIT=2
       Else
C        At field capacity, total soil moisture storage in layer 1
C        (unsaturated zone) in cm  = UF

         UF=fc(id,1)*dep
       if (uf .lt. 1.) then
         NIT = 500
       else
         ENIT1=20.*INFIL(ICell)*0.10/UF
         ENIT2=20. * Ks(id,1) / UF
         ENIT3=2.
         NIT=MAX1(ENIT1+0.9,ENIT2+0.9,ENIT3)
       end if
      ENDIF

       IF(NIT.LT.2) NIT = 2
       IF(NIT.GT.1000) NIT=1000
       H=1./FLOAT(NIT)

       DO 20 JJ=1,NIT

         uzone1(icell) = uzone1(icell) +infil(icell)*0.1*H

         if (uuzone1(icell) .ne. 0.) then
         uuzone1(icell) = uuzone1(icell)+infil(icell)*0.10*H
         smc1(icell)    = uuzone1(icell)/dep
         endif

         if (smc1(icell) .le. fc(id,1)) then
         drain1 = 0.

         elseif (smc1(icell) .lt. ssmc(id,1)) then

         Se = (smc1(icell)-rsmc(id,1))/(ssmc(id,1)-rsmc(id,1))
         drain1 = KS(id,1)*(Se**0.5)*( 1- Se*(Se**(-1/wm(id,1))-1)
     >     **wm(id,1) )**2

         uuZONE1(ICell) = uuZONE1(icell) - DRAIN1*H

         if(uuzone1(icell) .lt. 0)  then
         uuzone1(icell)=fc(id,1)*dep
         drain1 = (smc1(icell)-fc(id,1))*dep/H
         endif
```

```
          else
          drain1 = infil(icell)*0.1
          uuzone1(icell) = 0.
          smc1(icell) = ssmc(id,1)

          endif

C ---       Sum of the daily drainage in cm/day from LAYER 1

          UDRAIN1=UDRAIN1+DRAIN1*H

 20     CONTINUE

          udrain(icell) = udrain1

C ---   If unsaturated zone has two or three layers

      ELSE IF(LAYER.EQ. 2 .or. layer .EQ. 3) THEN

        dout = uzone1(icell) + infil(icell)*0.10
        udrain1=0.
        smc1(icell)=dout/dep

       IF(INFIL(ICell).LT. 1. .AND. smc1(icell).LT. rsmc(id,1)) THEN
          NIT=2
       ELSE

C        At field capacity, total soil moisture storage in layer 1
C        (unsaturated zone) = UF

         UF=fc(id,1)*40.
         if (uf .lt. 1. ) then
         nit = 1000
         else
           ENIT1=20.*INFIL(ICell)*0.10/UF
           ENIT2=20.* Ks(id,1) / UF
           ENIT3=2.
           NIT=MAX1(ENIT1+0.9,ENIT2+0.9,ENIT3)
         end if
       ENDIF
         IF(NIT.LT.2) NIT = 2
         IF(NIT.GT.1000) NIT=1000
         H=1./FLOAT(NIT)

         DO 30 JJ=1, NIT

           uzone1(icell) = uzone1(icell) + infil(icell)*0.10*H

           if (uuzone1(icell) .ne. 0.) then
           uuzone1(icell) = uuzone1(icell)+infil(icell)*0.10*H
           smc1(icell) = uuzone1(icell)/40.0
           endif

           if (smc1(icell) .le. fc(id,1) ) then

           drain1=0.0

           elseif (smc1(icell) .lt. ssmc(id,1)) then

           Se = (smc1(icell)-rsmc(id,1))/(ssmc(id,1)-rsmc(id,1))
           DRAIN1 = KS(id,1)*(Se**0.5)*( 1- Se*(Se**(-1/wm(id,1))-1)
     >           **wm(id,1) )**2
           uuZONE1(ICell) = uuZONE1(icell) - DRAIN1*H
           uzone1(icell) = uzone1(icell) - drain1*H
```

```
          if(uuzone1(icell) .lt. 0.)  then
           uuzone1(icell)=fc(id,1)*40.
          drain1 = (smc1(icell)-fc(id,1))*40./H
          uzone1(icell) = uuzone1(icell)
          endif

          else

C.....    Layer 1 is saturated at this time step (perched water water table)

          uuzone1(icell) = 0.
          smc1(icell) = ssmc(id,1)
          uzone1(icell) = ssmc(id,1)*40.
          drain1 =(smc1(icell)-ssmc(id,1))*40./H

          endif

C ---       Sum of the day
          UDRAIN1=UDRAIN1+DRAIN1*H

 30       CONTINUE

C --- If unsaturated zone layer= 2, Route water content in layer 2
C
     If (layer .eq. 2) then

      udrain2 = 0.

      IF(udrain1 .LT. 0.10. AND. smc2(icell).LT. rsmc(id,2)) THEN
        NIT=2
      ELSE

C       At field capacity, total soil moisture storage in layer 1
C       (unsaturated zone) = UF

         UF=fc(id,2)*(dep-40.0)
        if (uf .lt. 1.) then
         nit = 1000
        else
         ENIT1=20.*udrain1 / UF
         ENIT2=20. * Ks(id,2) / UF
         ENIT3=2.
         NIT=MAX1(ENIT1+0.9,ENIT2+0.9,ENIT3)
        endif

      ENDIF
       IF(NIT.LT.2) NIT = 2
       IF(NIT.GT.1000) NIT=1000
       H=1./FLOAT(NIT)

      DO 40 JJ=1,NIT

         uzone2(icell) = uzone2(icell) + udrain1*H

         if (uuzone2(icell) .ne. 0.) then
         uuzone2(icell) = uuzone2(icell)+ udrain1*H
         smc2(icell) = uuzone2(icell)/(dep-40.0)
         endif

         IF (smc2(icell).LE. fc(id,2)) then

         DRAIN2=0.

         Else if ( smc2(icell) .lt. ssmc(id,2) ) then
```

```
          Se = (smc2(icell)-rsmc(id,2))/(ssmc(id,2)-rsmc(id,2))
          DRAIN2 = KS(id,2)*(Se**0.5)*( 1- Se*(Se**(-1/wm(id,2))-1)
     >          **wm(id,2) )**2
          uuZONE2(ICell) = uuZONE2(icell)-DRAIN2*H

          if(uuzone2(icell) .lt. 0.) then
          uuzone2(icell)=fc(id,2)*(dep-40.)
          drain2 = (smc2(icell)-fc(id,2))*(dep-40.)/H
          endif
          else

          drain2 = udrain1
          uuzone2(icell) = 0.
          smc2(icell) = ssmc (id,2)

          endif

C ---- Sum of the drainage in the day

          udrain2=udrain2+drain2*H

  40      CONTINUE

          Udrain(icell) = udrain2

C.... If layer =3 , calculate drainage with same procedure as layer=2

        Else

C --- Route water content in layer 2

       IF(udrain1 .LT.0.1 .AND. smc2(icell).LT. rsmc(id,2)) THEN
         NIT=2
         ELSE

C         At field capacity, total soil moisture storage in layer 1
C         (unsaturated zone) = UF

          UF=fc(id,2)*25.0
          if (uf .lt. 1.) then
          NIT = 1000
          else
          ENIT1=20.*udrain1 / UF
          ENIT2=20. * dout / UF
          ENIT3=2.
          NIT=MAX1(ENIT1+0.9,ENIT2+0.9,ENIT3)
          endif

        ENDIF
        IF(NIT.LT.2) NIT = 2
        IF(NIT.GT.1000) NIT=1000
        H=1./FLOAT(NIT)

        udrain2=0.

        DO 60 JJ=1,NIT

          uzone2(icell)=uzone2(icell)+udrain1*H

          if (uuzone2(icell) .ne. 0) then
          uuzone2(icell)=uuzone2(icell)+udrain1*H
          smc2(icell)=uuzone2(icell)/25.
          endif

          if (smc2(icell) .le. fc(id,2) )then
```

```
          Drain2=0.0

          else if (smc2(icell) .lt. ssmc(id,2)) then

          Se = (smc2(icell)-rsmc(id,2))/(ssmc(id,2)-rsmc(id,2))

          Drain2 = KS(id,2)*(Se**0.5)*( 1- Se*(Se**(-1/wm(id,2))-1)
     >          **wm(id,2) )**2

          uuZONE2(ICell) = uuZONE2(icell)-DRAIN2*H

          if(uuzone2(icell) .lt. 0.) then
          uuzone2(icell)=fc(id,2)*25.
          drain2 = (smc2(icell)-fc(id,2))*25./H
          uzone2 (icell) = uuzone2(icell)
          endif

          else

          smc2(icell) = ssmc(id,2)
          uuzone2(icell) = 0.
          uzone2(icell) = ssmc(id,2)*25.
          drain2 = (smc2(icell)-ssmc(id,2))*25./H

          endif

C ---      Sum of the day

          udrain2 = udrain2+drain2*H

  60    CONTINUE

        udrain3=0.

        IF( udrain2 .LT. 1. .AND. smc3(icell) .lt. fc(id,3)) THEN
         NIT=2
         ELSE
C          At field capacity, total soil moisture storage in layer 1
C          (unsaturated zone) = UF
           UF=fc(id,3)*(dep-65.0)

           if (UF .lt. 1.) then
           NIT=1000
           else
           ENIT1=20.*udrain2 / UF
           ENIT2=20. * dout / UF
           ENIT3=2.
           NIT=MAX1(ENIT1+0.9,ENIT2+0.9,ENIT3)
           endif
        ENDIF
         IF(NIT.LT.2) NIT = 2
         IF(NIT.GT.1000) NIT=1000
         H=1./FLOAT(NIT)

         DO 80 JJ=1, NIT

           uzone3(icell) =uzone3(icell) + udrain2*H

           if (uuzone3(icell) .NE. 0.) then
           uuzone3(icell) = uuzone3(icell) + udrain2*H
           smc3(icell)    = uuzone3(icell)/(dep-65.0)
           Endif

           if (smc3(icell) .le. fc(id,3)) then
            drain3=0.0
```

```
          else if (smc3(icell) .lt. ssmc(id,3)) then

          Se = (smc3(icell)-rsmc(id,3))/(ssmc(id,3)-rsmc(id,3))
          DRAIN3 = KS(id,3)*(Se**0.5)*( 1- Se*(Se**(-1/wm(id,3))-1)
     >          **wm(id,3) )**2

          uuzone3(icell) = uuzone3(icell) - drain3*H

          if(uuzone3(icell) .lt. 0)  then
          uuzone3(icell)=fc(id,3)*(dep-65.)
          drain3 = (smc3(icell)-fc(id,3))*(dep-65.)/H
          endif

          else
          uuzone3(icell) =0.
          smc3(icell) = ssmc(id,3)
          uzone3(icell) = ssmc(id,3)*(ath+dep-65.)
          drain3 = (smc3(icell)-ssmc(id,3))*(dep-65.)/H

          end if

C ---       Sum of the day

          UDRAIN3 = UDRAIN3+DRAIN3*H

  80      CONTINUE

          udrain(icell) = udrain3

        End if
       End if

90    PLAYER(ICell)=LAYER

100   CONTINUE

      RETURN
      END


$NOFLOATCALLS
$STORAGE:2
$DEBUG
C*************************************************************************C
C    5.0                                                                  C
C    *** SUBROUTINE COASGF ***                                            C
C    Simulate saturated ground water flow for one stress                  C
C    period (one day)                                                     C
C                                                                         C
C    Author:  M. G. McDonald and A. W. Harbaugh (1984)                    C
C             Modified by Chin-Hong Sun                                   C
C    Modified by Ge Sun , Dec 1995                                        C
C*************************************************************************C
      SUBROUTINE COASGF(IDAY)

      COMMON/X/ X(10000)
      COMMON/SHR/ IBOUND(30,30),W(50)
      COMMON/BASIC/ INRPS,IUNIT(12),MDAY(12),YEAR,IYEAR,IOUT,
     >          Ncell,NCOL,NROW,NLAY,NODES,TOTIM,DEGLAT,PEC
      INTEGER YEAR
      COMMON/LOCATE/ LCHOLD,LCHNEW,LCSTRT,LCDELR,LCDELC,LCSC1,
     >          LCHY,LCBOT,LCTOP,LCCC,LCCR,LCCV,LCUZDE,
     >          LCHCOF,LCRHS, lcuzone1,lcuzone2,lcuzone3
```

```
      COMMON/SGF/ DELT,NSTP,PERTIM,TRPY,KITER,HCNV,ILEVEL,
     >          KSTP,KPER,NRIVER,MXITER,NPARM,
     >          HCLOSE,ACCL,IPCALC,IPRSIP,IPRSOR,
     >          NSLICE,MBW,ISTRT

C --- Simulate each time step
      DO 100 KSTP=1, NSTP
C
C ---   Prepare and advance the time step
        CALL SGFADV(X(LCHOLD),X(LCHNEW))
C
C ---   Iteratively formulate and solve the equation
        DO 70 KITER=1,MXITER
C
C ---     Calculate branch conductances, and adds storage
C ---     terms to the accumulators in which HCOF and RHS
C ---     are formed

          CALL SGFBCF(X(LCHOLD),X(LCHNEW),X(LCHCOF),X(LCRHS),
     >     X(LCCC),X(LCCR))
C
C ---     Add recharge term from unsaturated zone and ET to RHS array
          CALL SGFRCH (X(LCRHS))
C
C ---     Add river runoff term to RHS array
          CALL SGFRIV(X(LCHNEW),X(LCHOLD),X(LCRHS),IDAY)
C
C ---     Choose one numerical method for approximate
C ---     solution of the formulated equation
          IF(IUNIT(7).GT.0) THEN
C
C ---       Perform one iteration of the Strongly Implicit
C ---       Procedure (SIP) algorithm for solving the flow
C ---       equation

            CALL SGFSIP(X(LCHNEW),X(LCCR),
     >       X(LCCC),X(LCCV),X(LCHCOF),X(LCRHS),icnvg)

          ELSEIF(IUNIT(8).GT.0) THEN
C
C ---       Perform one iteration of the Slice-Successive
C ---       Overrelaxation (SSOR) algorithm for solving
C ---       the flow equation
            CALL SGFSOR(X(LCHNEW),X(LCCR),X(LCCC),
     >          X(LCCV),X(LCHCOF),X(LCRHS))
          ENDIF
C
C ---     If convergence criterion was not met, stop iteration
          IF(ICNVG.EQ.1) go to 100

   70   CONTINUE
        KITER=MXITER

  100 CONTINUE
C
C --- Write daily ground water level to a file if flag is set, and
C --- calculate saturated ground water discharge below the streambeds
C --- through constant gradient boundary cells
      CALL SGFOUT(X(LCHNEW),X(LCCR),X(LCCC),IDAY)
C
C --- Return
      RETURN
      END
C*******************************************************************C
C   5.1                                 C
```

```
C   *** SUBROUTINE SGFADV ***                                C
C   Prepare and advance the time step                        C
C                                                            C
C************************************************************************C
    SUBROUTINE SGFADV(HOLD,HNEW)
    COMMON/BASIC/ INRPS,IUNIT(12),MDAY(12),YEAR,IYEAR,iout,
   >          Ncell,NCOL,NROW,NLAY,NODES,TOTIM,DEGLAT,PEC
    INTEGER YEAR
    COMMON/SGF/ DELT,NSTP,PERTIM,TRPY,KITER,HCNV,ILEVEL,
   >         KSTP,KPER,NRIVER,MXITER,NPARM,
   >         HCLOSE,ACCL,IPCALC,IPRSIP,IPRSOR,
   >         NSLICE,MBW,ISTRT
    DIMENSION HNEW(NCOL,NROW),HOLD(NCOL,NROW)
C
C --- Accumulate elapsed time in simulation (TOTIM) and in this
C --- stress period (PERTIM)
    TOTIM = TOTIM+DELT
    PERTIM = PERTIM+DELT
C
C --- Copy HNEW to HOLD
    DO 10 I=1,NROW
    DO 10 J=1,NCOL

    HOLD(J,I)=HNEW(J,I)

10  Continue

C --- RETURN
    RETURN
    END
C************************************************************************C
C   5.2                                                      C
C   *** SUBROUTINE SGFBCF ***                                C
C   This module calculates branch conductances which are not C
C   constant throughout the simulation, adds storage terms to C
C   the accumulators in which HCOF and RHS are formed.       C
C                                                            C
C************************************************************************C
    SUBROUTINE SGFBCF(HOLD,HNEW,HCOF,RHS, cc,cr)
    COMMON/SHR/ IBOUND(30,30),W(50)
    COMMON/BASIC/ INRPS,IUNIT(12),MDAY(12),YEAR,IYEAR,iout,
   >      Ncell,NCOL,NROW,NLAY,NODES,TOTIM,DEGLAT,PEC
    INTEGER YEAR
    COMMON/LAND/LADUSE(200,6),lid(200),cele(200),irow(200),icol(200)
    real laduse,cele
    integer irow,icol
    Common/head/ sy(16,15), CKS3(10),
   >         DELR(20),DELC(20),
   >         BOT(16,15),TOP(16,15), CV(20,20)

    COMMON/SGF/ DELT,NSTP,PERTIM,TRPY,KITER,HCNV,ILEVEL,
   >         KSTP,KPER,NRIVER,MXITER,NPARM,
   >         HCLOSE,ACCL,IPCALC,IPRSIP,IPRSOR,
   >         NSLICE,MBW,ISTRT
    COMMON/AREA/ TAREA,TWAREA,area(200),tuarea
    real tarea,twarea,tuarea,area
    COMMON/BUDGET/PRECIP(366),PE(200),PT(200),PET(366),
   >          PINT(200),WFLOW(366),UDRAIN(200),UZONE(200),AE(200),
   >          AT(200),AET(200),GFLOW(366),GDRAIN(200),REFLOW(366),
   >    GGFLOW(366),SINT(200),EVPT(200),sae(366),sat(366),sevpt(366),
   >          LEAK(200), MWT(366), MID(366)
    integer MID
    real leak,MWT

    COMMON/UZON/smc1(200),smc2(200),smc3(200),uuzone1(200),
```

```
     > uuzone2(200),uuzone3(200)
      Real smc1,smc2,smc3,uuzone1,uuzone2,uuzone3

      COMMON/SOIL/ssmc(5,5),KS(5,5),wa(5,5),wn(5,5),
     >          wb(5,5),wc(5,5),wm(5,5),FC(5,5),RSMC(5,5)
      REAL ssmc,KS,wa,wn,wb,wc,fc,rsmc
      real syy

      DIMENSION HNEW(NCOL,NROW),Hold(NCOL,NROW),Hcof(NCOL,NROW),
     > RHS(NCOL,NROW),CC(NCOL,NROW),CR(NCOL,NROW)
C
C --- For each cell initialize HCOF and RHS accumulators
      DO 5 I=1,NROW
      DO 5 J=1,NCOL
      HCOF(J,I)=0.
    5 RHS(J,I)=0.
C
C --- Add storage to HCOF and RHS
      ICell=0
      TLED = 1./DELT
      DO 10 I=1,NROW
      DO 10 J=1,NCOL

      IF(IBOUND(J,I).EQ.0) GO TO 10

       ICell=ICell+1
       wdep = (top (j,i)-hnew(j,i))*100.
       id=lid(icell)

C
C ---   Add storage terms to HCOF and RHS arrays

      If ( wdep .lt. 0. ) then
         RHO =  1.*area(icell)*1000.*1000.*TLED

       if ((-udrain(icell)+evpt(icell)*0.1).ge.abs(wdep) ) then


      Syy=EVPT(icell)/(abs(wdep)*10.+(evpt(icell)-abs(wdep)*10.)/
     >   (ssmc(id,1)-fc(id,1)))

         RHO= Syy*area(icell)*1000.*1000.*TLED

       endif

      Elseif ( wdep .ge. 0.  .and.
     >     udrain(icell)/(ssmc(id,1)-fc(id,1)) .gt. wdep ) then

      if ( wdep .le. 40.) then
       Syy=udrain(icell)/
     >    (udrain(icell)-wdep*(ssmc(id,1)-smc1(icell)) + wdep )

      elseif ( wdep .le. 65.) then
       Syy=udrain(icell)/( udrain(icell)-
     >        (40.*(ssmc(id,1)-smc1(icell))+(wdep-40.)*
     >        (ssmc(id,2)-smc2(icell)))+ wdep)
      else

       Syy=udrain(icell)/(udrain(icell)-
     >       (40.*(ssmc(id,1)-smc1(icell))+
     >       25.*(ssmc(id,2)-smc2(icell))+(wdep-65.)*
     >       (ssmc(id,3)-smc3(icell))) + wdep)
      endif

      RHO = Syy * area(icell) * 1000.0 * 1000.0 * TLED
```

```
      Else

       if ( wdep .lt. 40.) then
       Syy= Sy(id,1)
       elseif ( wdep .lt. 65.) then
       Syy = Sy(id,2)
       elseif ( wdep .lt. 120.) then
       Syy = Sy(id,3)
       else
       Syy= Sy(id,4)
       endif

        RHO = Syy*area(icell) * 1000.0 * 1000.0 * TLED
      Endif
      HCOF(J,I) = HCOF(J,I)-RHO
      RHS(J,I) = RHS(J,I)-RHO*Hold(J,I)
   10 CONTINUE
C
C --- Call BCF1A to calculate horizontal conductances
      CALL BCF1A(HNEW,CR,CC)

C --- Return
      RETURN
      END
C*******************************************************************************C
C    5.2.1                                        C
C    *** SUBROUTINE BCF1A ***                      C
C    Calculate transmissivity for each cell and then C
C    call BCF1B to calculate branch conductance    C
C                                                  C
C*******************************************************************************C
      SUBROUTINE BCF1A(HNEW,CR,CC)
      COMMON/SHR/ IBOUND(30,30),W(50)
      Common/head/ sy(16,15),
     >          CKS3(10),DELR(20),DELC(20)
     >          ,BOT(16,15),TOP(16,15),CV(20,20)
      COMMON/BASIC/ INRPS,IUNIT(12),MDAY(12),YEAR,IYEAR,iout,
     >      Ncell,NCOL,NROW,NLAY,NODES,TOTIM,DEGLAT,PEC
      INTEGER YEAR

      COMMON/SGF/ DELT,NSTP,PERTIM,TRPY,KITER,HCNV,ILEVEL,
     >          KSTP,KPER,NRIVER,MXITER,NPARM,
     >          HCLOSE,ACCL,IPCALC,IPRSIP,IPRSOR,
     >          NSLICE,MBW,ISTRT

      COMMON/SOIL/ssmc(5,5),KS(5,5),wa(5,5),wn(5,5),
     >wb(5,5),wc(5,5),wm(5,5),FC(5,5),RSMC(5,5)
      REAL ssmc,KS,wa,wn,wb,wc,fc,rsmc

      COMMON/LAND/LADUSE(200,6),lid(200),cele(200),irow(200),icol(200)
      real laduse,cele
      integer irow,icol

      DIMENSION HNEW(NCOL,NROW),CC(NCOL,NROW),CR(NCOL,NROW)
C
C --- Calculate transmissivity at each active cell.
C --- Transmissivity will be stored temporarily in the cc array.
      Icell = 0
      DO 10 I=1,NROW
      DO 10 J=1,NCOL
C
C ---   If cell is inactive then set T=0 and move on to next cell
        IF(IBOUND(J,I).NE.0) GO TO 20
        CC(J,I)=0.
```

```
      GO TO 10
20     Icell=icell+1
      ID=LID(Icell)
C
C ---   Calculate saturated thickness
      IF(HNEW(J,I).LT.BOT(J,I)) HNEW(J,I)=BOT(J,I)+0.001

      THCK = (HNEW(J,I)-BOT(J,I) )*100.
       Udep = (Top(J,I)-Hnew(j,i))*100.

C ---   Check to see if saturated thickness is greater than zero.
C       IF(THCK.LE.0) GO TO 100
C ---   If saturated thickness>0

      If (Udep .le. 0.) then
      CC(J,I)=THCK*400./10000.

      Elseif (Udep .lt. 40.) then
      CC(J,I) = ( (40.-udep)*Ks(id,I)+25.00*Ks(id,2)+
     >  (THCK-25.-40.+Udep)*Ks(id,3) )/10000.

      Elseif (Udep .lt. 65.) then
      CC(J,I) = ((25.0-Udep+40.)*Ks(id,2)+
     >  (THCK-25.-40.+Udep)*Ks(id,3) )/10000.

      Elseif (Udep .lt. 100.) then
      CC(J,I) = THCK*Ks(id,3)/10000.

      Else

      CC(J,I) =  THCK*CKS3(id)*Ks(id,3)/10000.

      Endif
C
  10 CONTINUE
C
C --- Compute horizontal branch conductances from transmissivity
     CALL BCF1B(CR,CC)
C
C --- Return
     RETURN
     END
C*******************************************************************************C
C    5.2.1.1                                    C
C    *** SUBROUTINE BCF1B ***                          C
C    Calculate horizontal-branch conductances from          C
C    transmissivity and cell dimensions.                C
C                                          C
C*******************************************************************************C
     SUBROUTINE BCF1B(CR,CC)

     Common/head/ sy(16,15), CKS3(10),DELR(20),DELC(20)
     >          ,BOT(16,15),TOP(16,15),CV(20,20)

     COMMON/BASIC/ INRPS,IUNIT(12),MDAY(12),YEAR,IYEAR,iout,
     >       Ncell,NCOL,NROW,NLAY,NODES,TOTIM,DEGLAT,PEC
     integer year
     COMMON/SGF/ DELT,NSTP,PERTIM,TRPY,KITER,HCNV,ILEVEL,
     >          KSTP,KPER,NRIVER,MXITER,NPARM,
     >          HCLOSE,ACCL,IPCALC,IPRSIP,IPRSOR,
     >          NSLICE,MBW,ISTRT

     DIMENSION CR(NCOL,NROW),CC(NCOL,NROW)

      YX=TRPY*2.
```

```
C
C --- For each cell calculate branch conductances from that cell
C --- to the one on the right and the one in front
      DO 40 I=1,NROW
      DO 40 J=1,NCOL
        T1=CC(J,I)

C
C ---   If T1=0 then set conductance equal to zero.
        IF(T1.NE.0) GO TO 10
        CR(J,I)=0.
        GO TO 40
C
C ---   If this is not the last column (rightmost) then calculate
C ---   branch conductance in the row direction (CR) to the right
C ....  by average the adjacent cells.

   10   IF(J.EQ.NCOL) GO TO 30
        T2=CC(J+1,I)
        CR(J,I)=2.*T2*T1*DELC(I)/(T1*DELR(J+1)+T2*DELR(J))
C
C ---   If this is not the last row (frontmost) then calculate
C ---   branch conductance in the column direction (CC) to the
C ---   front.
   30   IF(I.EQ.NROW) GO TO 40
        T2=CC(J,I+1)
        CC(J,I)=YX*T2*T1*DELR(J)/(T1*DELC(I+1)+T2*DELC(I))

   40 CONTINUE
C
C --- Return
      RETURN
      END
C*************************************************************************C
C    5.3                                    C
C    *** SUBROUTINE SGFRCH ***                          C
C    Add recharge terms generated from unsaturated zone to        C
C    RHS array                                    C
C                                          C
C*************************************************************************C
      SUBROUTINE SGFRCH (RHS)

$include:'com.for'

      DIMENSION  RHS(NCOL,NROW)

      ICell=0
      DO 10 IR=1,NROW
      DO 10 IC=1,NCOL

C ---   If cell is external there is no recharge into it.
        IF(IBOUND(IC,IR).EQ.0) GO TO 10
        ICell=ICell+1
C
C ---   Subtract recharge rate from RHS array; RECHAR is in the unit of m3/day;
C ...   UDRAIN in cm/day, area in KM2;
        RECHAR=UDRAIN(ICell)*area(icell)*10000.
        RHS(IC,IR)=RHS(IC,IR)-RECHAR

C ---   Add ground water evapotranspiration to RHS array
        EVOUT=EVPT(ICell)*area(ICell)*1000.
        RHS(IC,IR)=RHS(IC,IR)+EVOUT

   10 CONTINUE
```

```
C --- Return
      RETURN
      END
C-----------------------------------------------------------------------C
C   5.4                                        C
C   *** SUBROUTINE SGFRIV ***                              C
C   Add river seepage term to RHS and HCOF arrays              C
C                                              C
C-----------------------------------------------------------------------C
      SUBROUTINE SGFRIV(HNEW,hold,RHS,IDAY)
      COMMON/SHR/ IBOUND(30,30),W(50)
      COMMON/BASIC/ INRPS,IUNIT(12),MDAY(12),YEAR,IYEAR,iout,
     >          Ncell,NCOL,NROW,NLAY,NODES,TOTIM,DEGLAT,PEC
      INTEGER YEAR
      COMMON/BUDGET/ PRECIP(366),PE(200),PT(200),PET(366),PINT(200),
     >           WFLOW(366),UDRAIN(200),UZONE(200),AE(200),AT(200),
     >           AET(200),GFLOW(366),GDRAIN(200),REFLOW(366),
     >   GGFLOW(366),SINT(200),EVPT(200),sae(366),sat(366),sevpt(366),
     >           LEAK(200),MWT(366), MID(366)
      Integer MID
      real leak,MWT

      COMMON/AREA/ TAREA,TWAREA, area(200),tuarea
      COMMON/SGF/ DELT,NSTP,PERTIM,TRPY,KITER,HCNV,ILEVEL,
     >         KSTP,KPER,NRIVER,MXITER,NPARM,
     >         HCLOSE,ACCL,IPCALC,IPRSIP,IPRSOR,
     >         NSLICE,MBW,ISTRT
      COMMON/LAND/LADUSE(200,6),lid(200),cele(200),irow(200),icol(200)
      real laduse,cele
      integer irow,icol

      COMMON/STREAM/K1,K2,K3,Lc
      real K1,K2,K3,Lc
      Common/top/atop
C --- TSA (total saturated area, m2)
      real TSA, leakout,sflow

      DIMENSION  HNEW(NCOL,NROW),RHS(NCOL,NROW), Hold(NCOL,NROW)

C
C --- Calculate daily total discharge FLOW from measured
C --- stream flow
      IF(IUNIT(12).NE.0) THEN
        FLOW=REFLOW(IDAY)*TAREA*1000.
      ENDIF
C
C --- Process each cell to calculate ground water discharge
      I=0
      IGN = 0
      TSA = 0.
      Surdep= 0.
      Thead=0.

      DO 10 II=1,NROW
      DO 10 JJ=1,NCOL
C ---   If the cell is external, skip it
        IF(IBOUND(JJ,II).EQ.0) GO TO 10
          I=I+1
          Thead=Thead+Hnew(jj,ii)
C ---   Calculate total area of cells where runoff occurs

          IF(Hnew(JJ,II) .GE. Cele(I) ) THEN

          SURDEP = surdep + Hnew(jj,ii) - Cele(i)
```

```
        IGN = IGN + 1
        TSA = TSA + Area(i)

        ENDIF
10      Continue
        Ahead=Thead/I
        if (ign .gt. 0) then
        Asurdep = surdep/ign
        else
        asurdep =0.
        endif
C ---  Calculate total daily stream flow(m3), GGFLOW from the whole watershed
      Call Rivflo(sflow,Ahead)
      ggflow(iday) = sflow

      I=0
      DO 20 II=1,nrow
      DO 20 JJ=1,ncol
      IF(IBOUND(JJ,II) .NE.0) then
      I=I+1

C ----  Calculate surface water discharge from each cell and add to RHS

      If (hnew(jj,ii) .gt. cele(i) ) then

        DISCH = sflow*Area(i)/TSA
        GDRAIN(i) = DISCH

      Else
        GDRAIN(i)=0.
        DISCH =0.

      Endif

        RHS(JJ,II) = RHS(JJ,II) + DISCH

C ----  Calculate surfcae water discharge from each cell and add to RHS
        Call leakflo (hnew,jj,ii,leakout)

        RHS(JJ,II) = RHS(JJ,II) + leakout*area(i)*1000.
        leak(i) = leakout

      Endif

 20   CONTINUE
C
C --- Return
     RETURN
     END
C*******************************************************************************C
C    5.4.1                                          C
C    *** SUBROUTINE RIVFLO ***                              C
C    Calculate ground water discharge from ground water rating      C
C    curve                                          C
C                                                   C
C*******************************************************************************C
     SUBROUTINE RIVFLO(SFLOW, Ahead)

     COMMON/AREA/ TAREA,TWAREA, area(200),tuarea
     COMMON/STREAM/ K1,K2,K3,Lc
     Real K1, K2,K3,Lc
     Common/top/atop
     Real Atopp
     real Sflow
```

```
C ----Calaculate total streamflow from the watershed
C ----by an empirical function (m3/day)
      Atopp=atop - .600
      If (ahead .gt. atopp) then

        SFLOW = ( K1 * Exp((Ahead-atopp) * K2) )*TAREA*1000.

      Elseif ( ahead .ge. K3) then
       Sflow = (K1*(ahead-K3)/(atopp-K3)) * TAREA*1000.

      ElseIF (AHEAD .LT. K3) THEN

        SFLOW = 0.

      Endif

C --- Return
      RETURN
      END
C*************************************************************************C
C   5.4.2                                    C
C   *** SUBROUTINE LEAKFLO ***                          C
C   Calculate ground water discharge from ground water rating      C
C   curve                                    C
C                                           C
C*************************************************************************C
      SUBROUTINE LEAKFLO(hnew,jj,ii,leakout)
      COMMON/BASIC/ INRPS,IUNIT(12),MDAY(12),YEAR,IYEAR,iout,
     >          Ncell,NCOL,NROW,NLAY,NODES,TOTIM,DEGLAT,PEC
      INTEGER YEAR

      COMMON/STREAM/ K1,K2,K3,Lc
      real K1, K2,k3,Lc

      real leakout
      Common/head/ sy(16,15),CKS3(10),DELR(20),DELC(20),
     >          BOT(16,15),TOP(16,15), CV(20,20)

      dimension Hnew(ncol,nrow)

      leakout = Lc * (hnew(jj,ii)-bot(jj,ii))**3

      if (hnew(jj,ii) .le. bot(jj,ii) ) leakout=0.

      Return
      end


C*************************************************************************C
C   5.5                                    C
C   *** SUBROUTINE SGFSIP ***                          C
C   Perform one iteration of the strongly implicit procedure      C
C   (SIP) algorithm for solving the flow equation.          C
C                                           C
C*************************************************************************C
      SUBROUTINE SGFSIP(HNEW,CR,CC,CV,HCOF,RHS,icnvg)
      COMMON/SHR/ IBOUND(30,30),W(50)
      COMMON/BASIC/ INRPS,IUNIT(12),MDAY(12),YEAR,IYEAR,iout,
     >          Ncell,NCOL,NROW,NLAY,NODES,TOTIM,DEGLAT,PEC
      INTEGER YEAR
      COMMON/SGF/ DELT,NSTP,PERTIM,TRPY,KITER,HCNV,ILEVEL,
     >          KSTP,KPER,NRIVER,MXITER,NPARM,
     >          HCLOSE,ACCL,IPCALC,IPRSIP,IPRSOR,
     >          NSLICE,MBW,ISTRT
      COMMON/DAY/ IM,ILM,IDD,IMONTH
```

```
      DIMENSION HNEW(nodes),CR(nodes), CC(nodes), CV(nodes),
     > HCOF(nodes),RHS(nodes),EL(1600),FL(1600),
     > GL(1600),V(1600), HDCG(1000), LRCH(3,1000)

      real S
C
C --- Calculate iteration parameters if flag is set.  Then
C --- clear the flag so that calculation is done only once.

      IF(IPCALC.NE.0)
     >    CALL SIP1A(CR,CC,CV,NPARM,NCOL,NROW,NLAY,IOUT)
      IPCALC=0
C
C --- Assign values to fields that are constant during an iteration
      DZERO=0.
      DONE=1.
      AC=ACCL
      NRC=NROW*NCOL
      NTH=MOD(KITER-1,NPARM)+1
      DITPAR=W(NTH)
C
C --- Initialize variable that tracks maximum head change during
C --- the iteration
      BIGG=0.
C
C --- Clear SIP work arrays.
      DO 100 I=1,NODES
        EL(I)=0.
        FL(I)=0.
        GL(I)=0.
  100 V(I)=0.
C
C --- Set normal/reverse equation ordering flag (1 or -1) and
C --- calculate indexes dependent on ordering
      IDIR=1
      IF(MOD(KITER,2).EQ.0)IDIR=-1
      IDNRC=IDIR*NRC
      IDNCOL=IDIR*NCOL
C
C --- Step through cells calculating intermediate vector V
C --- using forward substitution
      DO 150 K=1,NLAY
      DO 150 I=1,NROW
      DO 150 J=1,NCOL
C
C ---   Set up current cell location indexes.  These are dependent
C ---   on the direction of equation ordering.
        IF(IDIR.LE.0)GO TO 120
        II=I
        JJ=J
        KK=K
        GO TO 122
  120   II=NROW-I+1
        JJ=J
        KK=NLAY-K+1
C
C ---   Calculate 1 dimensional subscript of current cell and
C ---   skip calculations if cell is noflow or constant head
  122   N=JJ+(II-1)*NCOL+(KK-1)*NRC

        IF(IBOUND(JJ,II).EQ.0)GO TO 150
C
C ---   Calculate 1 dimensional subscripts for locating the 6
C ---   surrounding cells
        NRN=N+IDNCOL
```

```
      NRL=N-IDNCOL
      NCN=N+1
      NCL=N-1
      NLN=N+IDNRC
      NLL=N-IDNRC
C
C ---   Calculate I dimensional subscripts for conductance to the 6
C ---   surrounding cells.  These depend on ordering of equations.
      IF(IDIR.LE.0)GO TO 124
      NCF=N
      NCD=NCL
      NRB=NRL
      NRH=N
      NLS=N
      NLZ=NLL
      GO TO 126
  124   NCF=N
      NCD=NCL
      NRB=N
      NRH=NRN
      NLS=NLN
      NLZ=N
C
C ---   Assign variables in matrices A & U involving adjacent cells
C ---   neighbor is I row back
  126   B=DZERO
      ELNRL=DZERO
      FLNRL=DZERO
      GLNRL=DZERO
      BHNEW=DZERO
      VNRL=DZERO
      IF(I.EQ.1.OR.IBOUND(JJ,II).EQ.-1) GO TO 128
      B=CC(NRB)
      ELNRL=EL(NRL)
      FLNRL=FL(NRL)
      GLNRL=GL(NRL)
      BHNEW=B*HNEW(NRL)
      VNRL=V(NRL)
C
C ---   Neighbor is I row ahead
  128   H=DZERO
      HHNEW=DZERO
      IF(I.EQ.NROW.OR.IBOUND(JJ,II).EQ.-1) GO TO 130
      H=CC(NRH)
      HHNEW=H*HNEW(NRN)
C
C ---   Neighbor is I column back
  130   D=DZERO
      ELNCL=DZERO
      FLNCL=DZERO
      GLNCL=DZERO
      DHNEW=DZERO
      VNCL=DZERO
      IF(J.EQ.1.OR.IBOUND(JJ,II).EQ.-1) GO TO 132
      D=CR(NCD)
      ELNCL=EL(NCL)
      FLNCL=FL(NCL)
      GLNCL=GL(NCL)
      DHNEW=D*HNEW(NCL)
      VNCL=V(NCL)
C
C ---   Neighbor is I column ahead
  132   F=DZERO
      FHNEW=DZERO
      IF(J.EQ.NCOL.OR.IBOUND(JJ,II).EQ.-1) GO TO 134
```

```
      F=CR(NCF)
      FHNEW=F*HNEW(NCN)
C
C ---   Neighbor is 1 layer behind
  134   Z=DZERO
      ELNLL=DZERO
      FLNLL=DZERO
      GLNLL=DZERO
      ZHNEW=DZERO
      VNLL=DZERO
      IF(K.EQ.1.OR.IBOUND(JJ,II).EQ.-1) GO TO 136
      Z=CV(NLZ)
      ELNLL=EL(NLL)
      FLNLL=FL(NLL)
      GLNLL=GL(NLL)
      ZHNEW=Z*HNEW(NLL)
      VNLL=V(NLL)
C
C ---   Neighbor is 1 layer ahead
  136   S=DZERO
      SHNEW=DZERO
      IF(K.EQ.NLAY.OR.IBOUND(JJ,II).EQ.-1) GO TO 138
      S=CV(NLS)
      SHNEW=S*HNEW(NLN)
C
C ---   Calculate the negative sum of all conductances to neighboring
C ---   cells
  138   E=-Z-B-D-F-H-S
C
C ---   Calculate components of the upper and lower matrices, which
C ---   are the factors of matrix (A+B)
      AL=Z/(DONE+DITPAR*(ELNLL+FLNLL))
      BL=B/(DONE+DITPAR*(ELNRL+GLNRL))
      CL=D/(DONE+DITPAR*(FLNCL+GLNCL))
      AP=AL*ELNLL
      CP=BL*ELNRL
      GP=CL*FLNCL
      RP=CL*GLNCL
      TP=AL*FLNLL
      UP=BL*GLNRL
      HHCOF=HCOF(N)
c       print *,'N=',hhcof',N, hhcof
      DL=E+HHCOF+DITPAR*(AP+TP+CP+GP+UP+RP)-AL*GLNLL
     >    -BL*FLNRL-CL*ELNCL
      EL(N)=(F-DITPAR*(AP+CP))/DL
      FL(N)=(H-DITPAR*(TP+GP))/DL
      GL(N)=(S-DITPAR*(RP+UP))/DL
C
C ---   Calculate the residual
      RRHS=RHS(N)
      HNW=HNEW(N)
      HCFHNW=HNW*HCOF(N)
      RES=RRHS-ZHNEW-BHNEW-DHNEW-E*HNEW(N)-HCFHNW
     >    -FHNEW-HHNEW-SHNEW
C
C ---   Calculate the intermediate vector V
      V(N)=(AC*RES-AL*VNLL-BL*VNRL-CL*VNCL)/DL
C
  150 CONTINUE
C
C --- Step through each cell and solve for head change by back
C --- substitution
    DO 160 K=1,NLAY
    DO 160 I=1,NROW
    DO 160 J=1,NCOL
```

```
C
C ---  Set up current cell location indexes.  These are dependent
C ---  on the direction of equation ordering.
      IF(IDIR.LT.0) GO TO 152
      KK=NLAY-K+1
      II=NROW-I+1
      JJ=NCOL-J+1
      GO TO 154
  152 KK=K
      II=I
      JJ=NCOL-J+1
C
C ---  Calculate 1 dimensional subscript of current cell and
C ---  skip calculations if cell is noflow or constant head
  154 N=JJ+(II-1)*NCOL+(KK-1)*NRC
      IF(IBOUND(JJ,II).EQ.0)GO TO 160
C
C ---  Calculate 1 dimensional subscripts for the 3 neighboring cells
C ---  behind (relative to the direction of the back substitution
C ---  ordering) the current cell.
      NC=N+1
      NR=N+IDNCOL
      NL=N+IDNRC
C
C ---  Back substitute, storing head change in array V in place of
C ---  intermediate forward substitution values.
      ELXI=DZERO
      FLXI=DZERO
      GLXI=DZERO
      IF(JJ.NE.NCOL) ELXI=EL(N)*V(NC)
      IF(I.NE.1) FLXI=FL(N)*V(NR)
      IF(K.NE.1) GLXI=GL(N)*V(NL)
      VN=V(N)
      V(N)=VN-ELXI-FLXI-GLXI
C
C ---  Get the absolute head change. If it is max over cell so far.
C ---  Then save it along with cell indices and head change.
      TCHK=ABS(V(N))
      IF (TCHK.LE.BIGG) GO TO 155
      BIGG=TCHK
      BIG=V(N)
      IB=II
      JB=JJ
      KB=KK
C
C ---  Add head change this iteration to head from the previous
C ---  iteration to get a new estimate of head.
  155 XI=V(N)
      HNEW(N)=HNEW(N)+XI
C
  160 CONTINUE
C
C --- Store the largest absolute head change (this iteration) and
C --- its location.
    HDCG(KITER)=BIG
    LRCH(1,KITER)=KB
    LRCH(2,KITER)=IB
    LRCH(3,KITER)=JB
    ICNVG=0
    IF(BIGG.LE.HCLOSE) ICNVG=1

C
C --- Return
  600 RETURN
    END
```

```
C*****************************************************************C
C   5.5.1                                C
C   *** SUBROUTINE SIP1A ***                        C
C   Calculate an iteration-parameter seed using model        C
C   conductance values and cell dimensions.              C
C                                        C
C*****************************************************************C
    SUBROUTINE SIP1A(CR,CC,CV,NPARM,NCOL,NROW,NLAY,IOUT)
    COMMON/SHR/ IBOUND(30,30),W(50)
C
    DIMENSION CR(NCOL,NROW),CC(NCOL,NROW),CV(NCOL,NROW)
C
    DOUBLE PRECISION DWMIN,AVGSUM
C
C --- Calculate constants and initialize variables
    PIEPIE=9.869604
    R=NROW
    C=NCOL
    L=NLAY
    CCOL=PIEPIE/(2.*C*C)
    CROW=PIEPIE/(2.*R*R)
    CLAY=PIEPIE/(2.*L*L)
    WMINMN=1.
    AVGSUM=0.
    NODES=0
C
C --- Loop through all cells, calculating a seed for each cell
C --- that is active
    DO 100 I=1,NROW
    DO 100 J=1,NCOL
      IF(IBOUND(J,I).EQ.0) GO TO 100
C
C ---   Conductance from this cell
C ---   to each of the 6 adjacent cells
      D=0.
      IF(J.NE.1) D=CR(J-1,I)
      F=0.
      IF(J.NE.NCOL) F=CR(J,I)
      B=0.
      IF(I.NE.1) B=CC(J,I-1)
      H=0.
      IF(I.NE.NROW) H=CC(J,I)
      Z=0.
      S=0.
C
C ---   Find the maximum and minimum of the 2 conductance coefficients
C ---   in each principal coordinate direction
      DFMX=AMAX1(D,F)
      BHMX=AMAX1(B,H)
      ZSMX=AMAX1(Z,S)
      DFMN=AMIN1(D,F)
      BHMN=AMIN1(B,H)
      ZSMN=AMIN1(Z,S)
      IF(DFMN.EQ.0.) DFMN=DFMX
      IF(BHMN.EQ.0.) BHMN=BHMX
      IF(ZSMN.EQ.0.) ZSMN=ZSMX
C
C ---   Calculate a seed in each principal coordinate direction
      WCOL=1.
      IF(DFMN.NE.0.) WCOL=CCOL/(1.+(BHMX+ZSMX)/DFMN)
      WROW=1.
      IF(BHMN.NE.0.) WROW=CROW/(1.+(DFMX+ZSMX)/BHMN)
      WLAY=1.
      IF(ZSMN.NE.0.) WLAY=CLAY/(1.+(DFMX+BHMX)/ZSMN)
C
```

```
C ---   Select the cell seed, which is the minimum seed of the 3.
C ---   Select the minimum seed over the whole cell.
      WMIN=AMIN1(WCOL,WROW,WLAY)
      WMINMN=AMIN1(WMINMN,WMIN)
C
C ---   Add the cell seed to the accumulator AVGSUM for use
C ---.  in getting the average seed.
      DWMIN=WMIN
      AVGSUM=AVGSUM+DWMIN
      NODES=NODES+1
C
  100 CONTINUE
C
C --- Calculate the average seed of the cell seeds, and print
C --- the average and minimum seeds.
    TMP=NODES
    AVGMIN=AVGSUM
    AVGMIN=AVGMIN/TMP
    WRITE(IOUT,101) AVGMIN,WMINMN
  101 FORMAT(1H0,'AVERAGE SEED =',F11.8/1X,'MINIMUM SEED =',F11.8)
C
C --- Calculate and print iteration parameters from the average seed
    P1=-1.
    P2=NPARM-1
    DO 50 I=1,NPARM
    P1=P1+1.
   50 W(I)=1.-AVGMIN**(P1/P2)
    WRITE(IOUT,150) NPARM,(W(J),J=1,NPARM)
  150 FORMAT(1H0,/,I5,' ITERATION PARAMETERS CALCULATED FROM',
   >     ' AVERAGE SEED:'//(10X,6E15.7))
C
C --- Return
    RETURN
    END
C*************************************************************************C
C    5.6                                    C
C    *** SUBROUTINE SGFSOR ***                          C
C    Perform one iteration of the slice-successive over-          C
C    relaxation (SSOR) algorithm for solving the flow equation       C
C                                           C
C*************************************************************************C
    SUBROUTINE SGFSOR(HNEW,CR,CC,CV,HCOF,RHS)
    COMMON/SHR/ IBOUND(30,30),W(50)
    COMMON/BASIC/ INRPS,IUNIT(12),MDAY(12),YEAR,IYEAR,iout,
   >          Ncell,NCOL,NROW,NLAY,NODES,TOTIM,DEGLAT,PEC
    INTEGER YEAR
    COMMON/SGF/ DELT,NSTP,PERTIM,TRPY,KITER,HCNV,ILEVEL,
   >         KSTP,KPER,NRIVER,MXITER,NPARM,
   >         HCLOSE,ACCL,IPCALC,IPRSIP,IPRSOR,
   >         NSLICE,MBW,ISTRT
    COMMON/DAY/ IM,ILM,IDD,IMONTH
C
    DIMENSION HNEW(NCOL,NROW),CR(NCOL,NROW), CC(NCOL,NROW),
   >  CV(NCOL,NROW), HCOF(NCOL,NROW), RHS(NCOL,NROW),
   >  HDCG(1000), LRCH(3,1000),A(2,1000),RES(1000),
   >  IEQPNT(1,1000)
C
C --- Calculate # of elements in compressed matrix A and
C --- initialize fields to save largest head change,
C --- MBW is maximum bandwidth of the coefficient matrix plus 1
C --- (i.e., number of layer plus 1), NSLICE = number of cells in
C --- slice, NA = number of elements in the compressed coefficient
C --- matrix (A)
    MBW=NLAY+1
    NSLICE=NCOL*NLAY
```

```
      NA=MBW*NSLICE
      BIG=0.
      ABSBIG=0.
      IB=0
      JB=0
      KB=0
C
C --- Process each slice
      DO 500 I=1,NROW
C
C ---   Clear A
        DO 110 J=1,NSLICE
        DO 110 K=1,MBW
  110   A(K,J)=0.
C
C ---   Assign a sequence # to each variable head cell.
        NEQT=0
        DO 200 J=1,NCOL
        DO 200 K=1,NLAY
          IEQPNT(K,J)=0
          IF(IBOUND(J,I).EQ.0) GO TO 200
          NEQT=NEQT+1
          IEQPNT(K,J)=NEQT
  200   CONTINUE
C
C ---   For each cell load matrix A and vector RES
        DO 300 J=1,NCOL
        DO 300 K=1,NLAY
C
C ---     If sequence # is 0 (cell is external) go on to next cell
          NEQ=IEQPNT(K,J)
          IF(NEQ.EQ.0) GO TO 300
C
C ---     Initialize accumulators EE and R
          EE=0.
          R=RHS(J,I)
C
C ---     If node to left subtract terms from EE and R
          IF(J.EQ.1.OR.IBOUND(J,I).EQ.-1) GO TO 120
          DP=CR(J-1,I)
          R=R-DP*HNEW(J-1,I)
          EE=EE-DP
C
C ---     If node to right subtract terms from EE & R, move COND to A
  120     IF(J.EQ.NCOL.OR.IBOUND(J,I).EQ.-1) GO TO 125
          SP=CR(J,I)
          DP=SP
          R=R-DP*HNEW(J+1,I)
          EE=EE-DP
          NXT=IEQPNT(K,J+1)
          IF(NXT.GT.0) A(1+NXT-NEQ,NEQ)=SP
C
C ---     If node to rear subtract terms from EE and R
  125     IF(I.EQ.1.OR.IBOUND(J,I).EQ.-1) GO TO 130
          DP=CC(J,I-1)
          R=R-DP*HNEW(J,I-1)
          EE=EE-DP
C
C ---     If node to front subtract terms from EE and R
  130     IF(I.EQ.NROW.OR.IBOUND(J,I).EQ.-1) GO TO 132
          DP=CC(J,I)
          R=R-DP*HNEW(J,I+1)
          EE=EE-DP
C
C ---     If node above subtract terms from EE and R
```

```
 132    IF(K.EQ.1.OR.IBOUND(J,I).EQ.-1) GO TO 134
        DP=CV(J,I)
        R=R-DP*HNEW(J,I)
        EE=EE-DP
C
C ---   If node below subtract terms from EE & R and move COND to A
 134    IF(K.EQ.NLAY.OR.IBOUND(J,I).EQ.-1) GO TO 136
        SP=CV(J,I)
        DP=SP
        R=R-DP*HNEW(J,I)
        EE=EE-DP
        IF(IEQPNT(K+1,J).GT.0) A(2,NEQ)=SP
C
C ---   Move EE into A, subtract EE times last head from R
C ---   to get RES
 136    HHCOF=HCOF(J,I)
        A(1,NEQ)=EE+HHCOF
        HNW=HNEW(J,I)
        HCFHNW=HNW*HCOF(J,I)
        RES(NEQ)=R-EE*HNEW(J,I)-HCFHNW
 300    CONTINUE
C
C ---   If no equations go to next slice, if one equation solve
C ---   directly, if 2 equations call SOR1A to solve for first
C ---   estimate of head change for this iteration.
      IF(NEQT.LT.1) GO TO 500
      IF(NEQT.EQ.1) RES(1)=RES(1)/A(1,1)
      IF(NEQT.GE.2) CALL SOR1A(A,RES,NEQT,NA,MBW)
C
C ---   For each cell in slice calculate final head change then head.
      DO 400 J=1,NCOL
      DO 400 K=1,NLAY
        NEQ=IEQPNT(K,J)
        IF(NEQ.EQ.0) GO TO 400
C
C ---     Multiply first estimate of head change by relax factor to
C ---     get final estimate of head change for this iteration.
        DH=RES(NEQ)*ACCL
        DIFF=DH
C
C ---     Add final estimate to head from last iteration to get head
C ---     for this iteration.
        HNEW(J,I)=HNEW(J,I)+DIFF
C
C ---     Save final head change if it is the largest
        ABSDH=ABS(DH)
        IF(ABSDH.LE.ABSBIG) GO TO 400
        ABSBIG=ABSDH
        BIG=DH
        IB=I
        JB=J
        KB=K
 400    CONTINUE
C
C
 500 CONTINUE
C
C --- Save largest head change for this iteration
     HDCG(KITER)=BIG
     LRCH(1,KITER)=KB
     LRCH(2,KITER)=IB
     LRCH(3,KITER)=JB
C
C --- If largest head change is smaller than closure then set
C --- converge flag (ICNVG) equal to 1.
```

```
      ICNVG=0
      IF(ABSBIG.LE.HCLOSE) ICNVG=1
C
C --- If not converged and not exceeded iterations then return
      IF(ICNVG.EQ.0 .AND. KITER.NE.MXITER) RETURN
C
C --- Return
  700 RETURN
      END
C*****************************************************************************C
C    5.6.1                                C
C    *** SUBROUTINE SOR1A ***                          C
C    Solve a symmetric set of equations                C
C    A is coefficient matrix in compressed form          C
C    B is right hand side and is replaced by solution    C
C    N is number of equations to be solved             C
C    MBW is bandwidth of A                           C
C    NA is one-dimension size of A                     C
C                                       C
C*****************************************************************************C
      SUBROUTINE SOR1A(A,B,N,NA,MBW)
      DIMENSION A(NA),B(N)
C
      NM1=N-1
      MBW1=MBW-1
      ID=1-MBW
C
C --- Sequentially use each of the first N-1 rows as
C --- the pivot row.
      DO 20 I=1,NM1
C
C ---   Calculate the inverse of the pivot.
        ID=ID+MBW
        C1=1./A(ID)
        LD=ID
        L=I
C
C ---   For each row after the pivot row (the target row)
C ---   eliminate the column corresponding to the pivot.
        DO 15 J=1,MBW1
          L=L+1
          IF(L.GT.N) GO TO 20
          IB=ID+J
C
C ---     Calculate the factor needed to eliminate a term in the
C ---     target row.
          C=A(IB)*C1
          LD=LD+MBW
          LB=LD-1
C
C ---     Modify the rest of the terms in the target row.
          DO 10 K=J,MBW1
C
C ---       Subtract the factor times a term in the pivot row
C ---       from the corresponding column in the target row.
            LB=LB+1
            A(LB)=A(LB)-C*A(ID+K)
   10     CONTINUE
C
C ---     Modify the right side of the equation corresponding
C ---     to the target row.
          B(I+J)=B(I+J)-C*B(I)
   15   CONTINUE
   20 CONTINUE
      ID=ID+MBW
```

```
C
C --- Solve the last equation.
      B(N)=B(N)/A(1D)
C
C --- Working backwards solve the rest of the equations.
      DO 70 I=1,NM1
        1D=1D-MBW
C
C ---   Clear the accumulator SUM.
        SUM=0.0
        L=N-I
        MBW1M=MIN0(MBW1,I)
C
C ---   Add the known terms in equation L to SUM.
        DO 60 J=1,MBW1M
          SUM=SUM+A(ID+J)*B(L+J)
   60   CONTINUE
C
C ---   Solve for the one unknown in equation L.
        B(L)=(B(L)-SUM)/A(ID)
   70 CONTINUE
C
C --- RETURN
      RETURN
      END
C*************************************************************************C
C   5.7                                    C
C   *** SUBROUTINE SGFOUT ***                          C
C   Write daily ground water level to a file if IUNIT(11) = 1,      C
C   and calculate saturated ground water discharge below the       C
C   streambeds through constant gradient boundary cells            C
C                                          C
C*************************************************************************C
      SUBROUTINE SGFOUT(HNEW,CR,CC,IDAY)
      COMMON/SHR/ IBOUND(30,30),W(50)
      COMMON/BASIC/ INRPS,IUNIT(12),MDAY(12),YEAR,IYEAR,iout,
     >          Ncell,NCOL,NROW,NLAY,NODES,TOTIM,DEGLAT,PEC
      INTEGER YEAR
      COMMON/DAY/ IM,ILM,ID,IMONTH
      COMMON/AREA/ TAREA,TWAREA,  area(200),tuarea

      COMMON/BUDGET/ PRECIP(366),PE(200),PT(200),PET(366),PINT(200),
     >          WFLOW(366),UDRAIN(200),UZONE(200),AE(200),AT(200),
     >          AET(200),GFLOW(366),GDRAIN(200),REFLOW(366),
     >          GGFlow(366),SINT(200),EVPT(200),sae(366),sat(366),
     >          sevpt(366),Leak(200), MWT(366), MID(366)
      Integer MID
      real leak,MWT

      COMMON/SGF/ DELT,NSTP,PERTIM,TRPY,KITER,HCNV,ILEVEL,
     >        KSTP,KPER,NRIVER,MXITER,NPARM,
     >        HCLOSE,ACCL,IPCALC,IPRSIP,IPRSOR,
     >        NSLICE,MBW,ISTRT

      DIMENSION HNEW(NCOL,NROW),CR(NCOL,NROW),CC(NCOL,NROW)
C
C --- Calculate saturated ground water discharge below the streambeds
C --- through faces fo constant gradient boundary cells
      TGFLOW = 0.
      DO 10 I=1,NROW
      DO 10 J=1,NCOL
C ---   Initialize flow buffers
        X1=0.
        X2=0.
        X3=0.
```

```
      X4=0.
C ---   For each constant gradient boundary cell, calculate flow
C ---   through that face that connected to an inactive cell (i.e.,
C ---   cell located outside the watershed)
      IF(IBOUND(J,I).EQ.-1) THEN
C
C ---     Check left face
        IF(J.EQ.1) THEN
          IF(IBOUND(J+1,I).ne.0) THEN
            X1=(HNEW(J+1,I)-HNEW(J,I))*CC(J,I)
          ENDIF
        ELSEIF(J.EQ.NCOL) THEN
          X1=0.
        ELSEIF(IBOUND(J-1,I).EQ.0.AND.IBOUND(J+1,I).ne. 0) THEN
            X1=(HNEW(J+1,I)-HNEW(J,I))*CC(J,I)
        ENDIF
C
C ---     Check right face
        IF(J.EQ.1) THEN
          X2=0.
        ELSEIF(J.EQ.NCOL) THEN
          IF(IBOUND(J-1,I).NE. 0) THEN
            X2 =(HNEW(J-1,I)-HNEW(J,I))*CC(J-1,I)
          ENDIF
        ELSEIF(IBOUND(J+1,I).EQ.0.AND.IBOUND(J-1,I).NE.0) THEN
            X2=(HNEW(J-1,I)-HNEW(J,I))*CC(J,I)
        ENDIF
C
C ---     Check rear face
        IF(I.EQ.1) THEN
          IF(IBOUND(J,I+1).NE.0) THEN
            X3=(HNEW(J,I+1)-HNEW(J,I))*CR(J,I)
          ENDIF
        ELSEIF(I.EQ.NROW) THEN
          X3=0.
        ELSEIF(IBOUND(J,I-1).EQ.0.AND.IBOUND(J,I+1).NE.0) THEN
            X3=(HNEW(J,I+1)-HNEW(J,I))*CR(J,I)
        ENDIF
C
C ---     Check front face
        IF(I.EQ.1) THEN
          X4=0.
        ELSEIF(I.EQ.NROW) THEN
          IF(IBOUND(J,I-1).NE.0) THEN
            X4=(HNEW(J,I-1)-HNEW(J,I))*CR(J,I-1)
          ENDIF
        ELSEIF(IBOUND(J,I+1).EQ.0.AND.IBOUND(J,I-1).NE.0) THEN
            X4=(HNEW(J,I-1)-HNEW(J,I))*CR(J,I)
        ENDIF
C
C ---     Accumulate total saturated ground water discharge below
C ---     streambeds throung constant gradient boundary cells
        TGFLOW=TGFLOW+X1+X2+X3+X4
      ENDIF
   10 CONTINUE

C --- Convert discharge to mm per day
    GFLOW(IDAY)= TGFLOW/(TAREA*1000.)

C
C --- If flag ILEVEL is equal to zero, RETURN.
    IF(ILEVEL.EQ.0) RETURN
C
C --- Write daily ground water level to a file
```

```
      WRITE(78,2000) IMONTH,ID,YEAR
 2000 FORMAT(I3,'-',I2,'-',I4)
      DO 20 I=1,NROW
        WRITE(78,2010) (HNEW(J,I),J=1,NCOL)
 2010   FORMAT(1X,19F7.3)
   20 CONTINUE
C
C --- Return
      RETURN
      END

$NOFLOATCALLS
$STORAGE:2
$DEBUG
C*************************************************************************C
C    6.0                                    C
C    *** SUBROUTINE COAAET ***                          C
C    Simulate daily actual evapotranspiration                C
C                                          C
C*************************************************************************C
      SUBROUTINE COAAET(IDAY,HNEW,uzone1,uzone2,uzone3)
      Real ATH, DEP

$include:'com.for'

      dimension Hnew(ncol,nrow)
      dimension uzone1(ncell),uzone2(ncell),uzone3(ncell)

     I=0
     DO 10 II=1,NROW
     DO 10 JJ=1,NCOL
       IF(IBOUND(JJ,II).EQ.0) GO TO 10
       I=I+1
       id =iid(i)

C ---   Calculate unsaturated zone depth (DEP) and aquifer thickness (ATH) in cm

       DEP=(TOP(JJ,II)-HNEW(JJ,II))*100.
       ATH=(hnew(jj,ii)-bot(jj,ii))*100.
       IF (Ath .lt. 0.) Ath=0.

       If (dep .ge. 65.) layer = 3
       If (dep .lt. 65.) layer = 2
       if (dep .le. 40.) layer = 1
       if (dep .le. 0. ) layer = 0

C
C ---   Calculate interception storage SINT
       IF(SINT(I).GE.PET(IDAY)) THEN
         SINT(I)= SINT(I)-PET(IDAY)
         EVPT(I)=0.

       ELSE
C ---     Assign SINT to a temperate variable TSINT
         TSINT=SINT(I)
C ---     Calculate residual evapotranspiration (RET)
         RET=PET(IDAY)-SINT(I)
         SINT(I)=0.

C ---   Calculate Potential Evaporation (PE), Potential Transpiration(PT),
C ---   and Possible Realized Transpiration (PRT)

       PE(i) = RET*exp(-CE1*lai(id,iday))
       PT(i) = RET-PE(i)
       PRT= PT(i)*(lai(id,iday)+1.12*CT1)/mlai(id,iday)*
```

```
     >     ttrd(id)/tmtrd(id)

C ---   Calculate vegetation transpiration from each layer and
C       evaporation from Layer 1 only

        IF(LAYER.EQ.3) THEN

C ---   Ground water level is lower than 65 cm
C ---   calcualte evaporation first

        If(dep .lt. 100.) then
        AE(i) = PE(i) * ( (100. - dep)/(100.-35.))**CE2
        Else
        AE(i) = 0.
        endif

        EXPO = CT2/PRT
        IF(EXPO.GT.31.) EXPO=31.

C ---     Calculate transpiration function F1, F2, F3
C ---     if water content is higher than field capacity, potential transpiration
C ---     is applied

        IF((fc(id,3)-uUZONE3(I)/(dep-65.)) .LE. 0. .or. dep .lt.100.
     >    .or. uuzone3(i) .eq. 0. ) then

          F3=1.
        ELSEIF( (uUZONE3(I)/(dep-65.)) .LE. rsmc(id,3) .or.
     >       uuzone3(i) .LT. 0.0) THEN

          F3=0.
        ELSE
          F3=1-( (fc(id,3)-uUZONE3(I)/(dep-65.) )/
     >        (fc(id,3)-rsmc(id,3)))**EXPO
        ENDIF

        IF((fc(id,2)-uUZONE2(I)/25.).LE.0 .or. uuzone2(i) .eq. 0.)
     >    then
          F2=1.
        ELSEIF((uUZONE2(I)/25.).LE. rsmc(id,2) .or. uuzone2(i)
     >    .LT. 0.) THEN
          F2=0.
        ELSE
          F2=1-((fc(id,2)-uUZONE2(I)/25.)/(fc(id,2)
     >      -rsmc(id,2)))**EXPO
        ENDIF
        IF((fc(id,1)-uUZONE1(I)/40.).LE.0. .or. uuzone1(i) .eq. 0.)
     >    THEN
         F1=1.
        ELSEIF((uUZONE1(I)/40.).LE. rsmc(id,1) .or. uuzone1(i)
     >    .LT. 0.) THEN
          F1=0.
        ELSE
          F1=1-((fc(id,1)-uUZONE1(I)/40.)/(fc(id,1)-rsmc(id,1)))
     >      **EXPO
        ENDIF
        E1 = AE(i)
        T1 = PRT*weight(id,1)*F1

C----   Calculate total ET loss from the aquifer, and CET is used to consider
C ----  WT drop by ET loss from upper layers

        uuzone1(I) = uuzone1(I)-CET*(E1+T1)*0.10
        uzone1(I) = uzone1(I)-CET*(E1+T1)*0.10
```

```
      T2 = PRT*WEIGHT(id,2)*F2
      uuzone2(I) = uuzone2(I)-CET*T2*0.10-(1-CET)*(E1+T1)*0.10
      uzone2(I) = uzone2(I) - CET*T2*0.10-(1-CET)*(E1+T1)*0.10

      T3 = PRT*WEIGHT(id,3)*F3*(dep-65.)/(ath+dep-65.)
      uuzone3(I) = uuzone3(I)-CET*T3*0.10 - (1-CET)*T2*0.10

      T3S = PRT*weight(id,3)*1.*ath/(ath+dep-65.)

      Uzone3(I)=uzone3(I)-T3S*0.10-T3*0.10-(1-CET)*T2*0.10

C -----   Calculate total water loss from the aquifer
      EVPT(I) = T3S + (1-CET)*T3
      AT(i) =T1+T2+T3+T3S

    Else if(LAYER.EQ.2) THEN
C ---  Ground water level is less than 65 cm in depth
C ---  calcualte evaporation first

      AE(i) = PE(i)* ( (100. - dep)/(100.-35.))**CE2
      EXPO = CT2/PRT

      IF(EXPO.GT.31.) EXPO=31.
C ---   Calculate transpiration function F1, F2, F3
      F3=1.
      F2=1.
      IF((fc(id,1)-uUZONE1(I)/40.) .LE. 0. .or. uuzone1(i) .eq.
     >      0. ) THEN
        F1=1.
      ELSEIF(( UUZONE1(I)/40.).LE. rsmc(id,1) .or. uuzone1(i)
     >   .LT. 0.) THEN
        F1=0.
      ELSE
        F1=1-((fc(id,1)-uUZONE1(I)/40.)/(fc(id,1)-rsmc(id,1)))
     >     **EXPO
      ENDIF
      E1 = AE(i)
      T1 = PRT*weight(id,1)*F1
      uuzone1(I) = uuzone1(I) - CET*(E1+T1)*0.10
      uzone1(I)  = uzone1(I)- CET*(E1+T1)*0.10

      T2 = PRT*WEIGHT(id,2)*F2*(dep-40.)/25.
      uuzone2(I) = uuzone2(I)-CET*T2*0.10 - (1-CET)*(E1+T1)*0.10
      T2S= PRT*WEIGHT(id,2)*(65.-dep)/25.
      uzone2(i) = uzone2(i)-T2S*0.10-T2*0.10-(1-CET)*(E1+T1)*0.10

      T3 = PRT*WEIGHT(id,3)*F3
      AT(i) = T1+T2+T2S+T3
      EVPT(I) = T3+T2S+(1-CET)*T2

    ElseIF(LAYER.EQ.1) THEN
C ---  Ground water level is lower than 35 cm
C ---  calcualte evaporation first

      If(dep .gt. 35.) then
      AE(i) = PE(i) * ( (100. - dep)/(100.-35.))**CE2
      Else
      AE(i) = PE(i)
      endif

      EXPO = CT2/PRT

      IF(EXPO.GT.31.) EXPO=31.
C ---   Calculate transpiration function F1, F2, F3
      F3=1.
```

```
      F2=1.

      IF((fc(id,1)-uUZONE1(l)/dep ) .LT.0. .or. dep .lt. 35.
     >   .or. uuzone1(i) .eq. 0 ) THEN
          F1=1.
      ELSEIF( uUZONE1(l)/dep .LE. rsmc(id,1) .or. uuzone1(i) .LT.
     >     0.) THEN
          F1=0.
      ELSE
          F1=1-((fc(id,1)-uUZONE1(I)/dep)/(fc(id,1)-rsmc(id,1)))
     >     **EXPO
      ENDIF

      E1 = AE(i)

      T1 = PRT*weight(1,id)*F1*(dep/40.)

      uuzone1(l) = uuzone1(I) - CET*(E1+T1)*0.10

      T1S = PRT*weight(1,id)*1.0*(40.-dep)/40.

      uzone1(I) = uzone1(I) - T1S*0.10 -(E1+T1)*0.10

      T2 = PRT*WEIGHT(id,2)*F2

      T3 = PRT*WEIGHT(id,3)*F3

      AT(i) = T1+T1S+T2+T3
      EVPT(I) = T3+T2+T1S +(1-CET)*(E1+T1)

C ---  If unsaturated zone depth = 0, i.e., LAYER=0, then,
C ---  AET=PET

    else

      AE(i)=PE(i)
      E1=AE(i)
      AT(I) = PRT
      EVPT(I)=AT(i)+AE(i)
      if (evpt(i) .lt. 0.) stop

    ENDIF


      AET(i) = AE(i) + AT(i)

    ENDIF


10   CONTINUE

C --- Return

    RETURN

    END


$NOFLOATCALLS
$STORAGE:2
$DEBUG


C*************************************************************************C
C   7.0                                                                   C
```

```
C    *** SUBROUTINE COADAY ***                              C
C    Calculate daily water budget                      C
C                                                C
C*****************************************************************************C
     SUBROUTINE COADAY(IDAY,hnew,uzone1,uzone2,uzone3)

     real xx,yy
$include: 'com.for'

     dimension Hnew(ncol, nrow)
     dimension uzone1(1000),uzone2(1000),uzone3(1000)
C --- Initialize accumulators
     SPRECI=0.
     SPINT=0.
     SWFLOW=0.
     SGDRAIN=0.
     SUAET=0.
     SUZON1=0.
     SUZON2=0.
     SUZON3=0.
     SUDRAI=0.
     SUHNEW=0.

     SuAT=0.
     SuAE=0.
     suevpt=0.
     suleak = 0.
C
C --- Find the summation of the hydrologic components

       DO 10 I=1,Ncell

       SPRECI=SPRECI+PRECIP(I)
       SPINT=SPINT+PINT(I)
       SUDRAI=SUDRAI+UDRAIN(I)
       SUZON1=SUZON1+UZONE1(I)
       SUZON2=SUZON2+UZONE2(I)
       SUZON3=SUZON3+UZONE3(I)
       SUAET=SUAET+AET(I)
       SWFLOW=SWFLOW+WFLOW(I)
       suat=suat+at(i)
       suae=suae+ae(i)
       Suevpt=suevpt+evpt(i)
       suleak = suleak + leak(i)

  10 CONTINUE

    DO 80 I=1,NROW
    DO 70 J=1,NCOL
     IF(IBOUND(J,I).NE.0) then
      SUHNEW=SUHNEW+HNEW(J,I)
      if (iday .eq. 159) then
        xx=(j-1)*50.+25.
        yy=(NROW*50.-25.)-(i-1)*50.
     write (120, 2200) xx, yy, HNEW(J,I)
 2200  Format (2F10.0, F10.3)

       Endif
     Endif
  70 Continue

  80 CONTINUE
C
C --- Calculate the average value of the hydrologic components
C --- across the watershed
```

```
      APRECI=SPRECI/Ncell
      APINT=SPINT/Ncell
      AUDRAIN=SUDRAI/Ncell
      AUZON1=SUZON1/Ncell
      AUZON2=SUZON2/Ncell
      AUZON3=SUZON3/Ncell
      AAET=SUAET/Ncell
      ARIV=GGflow(iday)/(TAREA*1000.)
      AWFLOW=SWFLOW/Ncell
      AHNEW=SUHNEW/Ncell

      aat=suat/ncell
      aae=suae/ncell
      aevpt=suevpt/ncell
      aleak =suleak/ncell
C
C --- Assign average values to holding arrays
      HPRECI(IDAY) = APRECI
      SIFLOW(IDAY)= AWFLOW + gflow(iday) + ARIV
      SSINT(IDAY) =APINT
      SAET(IDAY)  =AAET
      SUZONE(IDAY)=AUZON1+AUZON2+AUZON3
      SUDRAIN(IDAY)=AUDRAIN
      SAHNEW(IDAY)=AHNEW
      sae(iday)   = aae
      sat(iday)   = aat
      sevpt(iday) = aevpt
      sleak(iday) = aleak

C --- Print the daily water budget
      WRITE(79, 2000) year,Iday, IMONTH,IDD,APRECI,APINT,
     > PET(IDAY),Aevpt, aae, aat,AUZON1,AUZON2,AUZON3,AUDRAIN,
     > AHNEW,GFLOW(IDAY),ARIV, SIflow(iday),aleak
 2000 FORMAT(2I5, 2I3,2F6.1,2F6.1,2F6.1,3F6.2,
     >      F6.2,5F8.3)

      WRITE(100, 2015) year,Iday, aHNEW,siflow(iday)
 2015  format (2I5, F10.3,F10.1)

      WRITE(*,2018) year,Im,iday,precip(iday),
     >           siflow(iday),reflow(iday),ahnew
 2018 FORMAT(I6,I4,I6,F10.2,' Flow=',2F7.1,'      H=',F10.3,/)

C --- Return
      RETURN
      END
C*************************************************************************C
C    8.0                                        C
C    *** SUBROUTINE COABUG ***                          C
C    Perform monthly water budget calculation and statistical       C
C    analysis                                    C
C                                               C
C*************************************************************************C
      SUBROUTINE COABUG(ICOUNT,IDAY,INDEX)
      Double precision AAA,CCC,DDD,FFF

$include: 'com.for'

      Dimension SUM1(5),SUM2(5),F(5),BB(5),SQSUM1(5),SQSUM2(5),XBAR(5),
     >        YBAR(5),R(5)

C --- If index=2, do statistics for the whole simulation period.
C --- Icount= total simulation days

      IF(INDEX.EQ.2) ICOUNT=IDAY-ICOUNT+1
```

```
C
C --- Initialization
      SUM1(1)=0.
      SUM1(2)=0.
      SUM2(1)=0.
      SUM2(2)=0.
      SUM3=0.
      SUM4=0.
      SUM5=0.
      SUM6=0.
      SUM7=0.
      SUM8=0.
      SUM9=0.
      SUM10=0.
      SUM11=0.
      Sum12 =0.
      SQSUM1(1)=0.
      SQSUM1(2)=0.
      SQSUM2(1)=0.
      SQSUM2(2)=0.

      BB(1)=0.
      BB(2)=0.
      F(1)=0.
      F(2)=0.
      IMCOUNT=0
      SUMFLOW=0.
      SUMHEAD=0.
      DO 10 I=1,ICOUNT
C
C ---   Find the corresponding Julian day
        IIDAY=IDAY-ICOUNT+I

C ---   Calculate summation information for stream flow
C ---   statistical analysis
        IF (IUNIT(11) .EQ. 0) then
        write (90, 2060)
2060      format (' No measured data available for comparison')
        Else
        SUMFLOW=SUMFLOW+SIFLOW(IIDAY)
        SUMHEAD=SUMHEAD+SAHNEW(IIDAY)
        IF (MID(IIday) .NE. 0) then
          IMCOUNT=IMCOUNT+I

         Do 15, J=1,2
          If (j .eq. 1) then
          SUM1(j)   = SUM1(j) + REFLOW(IIDAY)
          SUM2(j)  = SUM2 (j) + SIFLOW(IIDAY)
          SQSUM1(j) = SQSUM1(j)+ REFLOW(IIDAY)**2
          SQSUM2(j) = SQSUM2(j)+ SIFLOW(IIDAY)**2
          BB(j)= BB(j)+REFLOW(IIDAY)*SIFLOW(IIDAY)
          F(j) = F(j) +(REFLOW(IIDAY)-SIFLOW(IIDAY))**2
        Else
          SUM1(j)  = SUM1(j) + MWT(IIDAY)
          SUM2 (j) = SUM2 (j) + SAHNEW(IIDAY)
          SQSUM1(j) = SQSUM1(j)+ MWT(IIDAY)**2
          SQSUM2(j) = SQSUM2(j)+ SAHNEW(IIDAY)**2
          BB(j) = BB(j) + MWT(IIDAY)*SAHNEW(IIDAY)
          F(j) = F(j) + (MWT(IIDAY)-SAHNEW(IIDAY) )**2
        Endif

15      Continue

        Endif
        Endif
```

```
C
C ---   Calculate monthly budget of the simulated hydrologic
C ---   components
      SUM3=SUM3+HPRECI(IIDAY)
      SUM4=SUM4+SAET(IIDAY)
      SUM5=SUM5+SSINT(IIDAY)
      SUM7=SUM7+SUDRAIN(IIDAY)
      SUM8=SUM8+GFLOW(IIDAY)
      sum9= sum9 + Sevpt(iiday)
      sum10 =sum10 + sae(iiday)
      sum11 =sum11 + sat(iiday)
      sum12 =sum12 + sleak(iiday)
   10 CONTINUE
C
C --- Statistical analysis of the simulated stream flow and water table

     IF (IUNIT(11) .NE. 0  .and. IMCOUNT .GT. 0) then

     DO 60 I = 1, 2
     XBAR(I) = SUM1(i)/IMCOUNT
     YBAR(i) = SUM2(i)/IMCOUNT
     DIFF=XBAR(I)-YBAR(I)
       If (Imcount .GT. 1 .and. I .eq. 1) then
       SDD1=F(i)-(SUM1(i)-SUM2(i))**2/IMCOUNT
       Sdd1=sdd1/imcount
       sdd1=sdd1/(imcount-1)
       ElseIf (Imcount .GT. 1 .and. I .eq. 2) then
       SDD2=F(i)-(SUM1(i)-SUM2(i))**2/IMCOUNT
       Sdd2=sdd2/imcount
       sdd2=sdd2/(imcount-1)
       Endif
     SUM1SQ=SUM1(i)**2
     SUM2SQ=SUM2(i)**2
     AAA=IMCOUNT*BB(I)-SUM1(i)*SUM2(i)
     CCC=ABS(Float(IMCOUNT)*SQSUM1(i)-SUM1SQ)**0.5
     DDD=ABS(Float(IMCOUNT)*SQSUM2(i)-SUM2SQ)**0.5
C
C --- R is Pearson correlation coefficient
     FFF=CCC*DDD
     IF(FFF .EQ. 0.000000) THEN
       R(i)=99.
     ELSE
       R(i)=AAA/(CCC*DDD)
     ENDIF
   60  Continue

       If(IMCOUNT .GT. 1 .and. index .eq. 1) then
       WRITE(90,2010) Imonth,YEAR,IMCOUNT,SUM1(1),SUM2(1),SDD1,R(1)
     >    ,XBAR(2),YBAR(2),SDD2,R(2)
 2010    FORMAT(I2,'-',I4, I4,3F7.1, F7.2,2F8.3,2F8.2 )

       Elseif ( IMCOUNT .EQ. 1 .and. index .eq. 1)  then
       WRITE(90,2015) Imonth,YEAR,IMCOUNT,SUM1(1),SUM2(1),R(1),XBAR(2)
     >             ,YBAR(2),R(2)
 2015   FORMAT(I2,'-',I4, I4,2F7.2,'   N/A',F7.1,2F8.3,'   N/A',F7.2)
       Elseif (index .eq.2)  then
       WRITE(90,2016) IMCOUNT,SUM1(1),SUM2(1),SDD1,R(1)
     >    ,XBAR(2),YBAR(2),SDD2,R(2)
 2016    FORMAT('Total  ',I4,3F7.1, F7.2,2F8.3, 2F8.2 )

       Endif

     ELSE
       WRITE(90,2018) Imonth,YEAR,IMCOUNT,SUM2(1),YBAR(2)
 2018   FORMAT(I2,'-',I4,I4,2X,'  N/A',F7.2,'  N/A  N/A   N/A',
```

```
     >F8.3,'  N/A   N/A')
      ENDIF

C --- Write monthly summary results to the file 'BUDGET.out'

      IF(INDEX.EQ.1) THEN
        SHEAD = SUMHEAD/icount
        WRITE(80,2000) IMONTH,YEAR,ICOUNT,SUMFLOW,SHEAD,
     >              SUM3,SUM4,SUM5,SUM7,SUM8,
     >  SUM9,SUM10,SUM11,SUM12

 2000  FORMAT(I2,'-',I4,I4,F8.1,F9.3,1x,9F7.1)

      ELSE
        SHEAD = SUMHEAD/icount
        WRITE(80,2025) ICOUNT,SUMFLOW,SHEAD,
     >              SUM3,SUM4,SUM5,SUM7,SUM8,
     >  SUM9,SUM10,SUM11,SUM12
 2025  FORMAT(/'Total    ', I3,F7.1,2x,F7.3,2x,9F7.1)

      IF(IUNIT(11) .NE. 0) THEN
C ---    Write the objective function
       If (Indexwt .eq. 0) then
       WRITE(90,2020) F(1)
 2020    FORMAT(/' OBJECTIVE FUNCTIONS FOR STREAMFLOW=',
     >   F8.1,/,' OBJECTIVE FUNCTIONS FOR water table not calculated'/)

       Elseif (Indexrun .eq. 0) then
       WRITE(90,2030) F(2)
 2030    FORMAT(/' OBJECTIVE FUNCTIONS FOR water table=',
     >   F6.2,/,'OBJECTIVE FUNCTIONS FOR Runoff not calculated'/)

       Else
        WRITE(90,2035) F(1), F(2)
 2035    FORMAT(/' OBJECTIVE FUNCTIONS FOR STREAMFLOW AND WATERTABLE
     >=',  F6.2, ' and ',F6.2,/)
       Endif

C ---    Calculate coefficient of determination
        DIFF1=0.
        DIFF2=0.
        DO 20 I=1,ICOUNT
          II=IDAY-ICOUNT+I
          If (MID(II) .EQ. 1) then
          DIFF1=DIFF1+(REFLOW(II)-XBAR(1))**2
          DIFF2=DIFF2+(MWT(II)-XBAR(2))**2
          ENDIF

  20    CONTINUE
      If (Diff1 .eq. 0. ) then
        WRITE(90,2040)
 2040    FORMAT(/' COEFFICIENT OF DETERMINATION for Stream Flow'
     >   ' was NOT calculated',)
        RSQUAR2=(DIFF2/ICOUNT-F(2)/ICOUNT)/(DIFF2/ICOUNT)
        WRITE(90,2050) RSQUAR2
 2045   FORMAT(' COEFFICIENT OF DETERMINATION for Water Table=',F10.3)

       Elseif (Diff2 .eq. 0. ) then
        WRITE(90,2050)
 2050    FORMAT(' COEFFICIENT OF DETERMINATION for Water Table'
     >   ' NOT calculated',)
        RSQUAR1=(DIFF1/ICOUNT-F(1)/ICOUNT)/(DIFF1/ICOUNT)
        WRITE(90,2080) RSQUAR1
 2080    FORMAT(' COEFFICIENT OF DETERMINATION for runoff=',F10.3/)
       Else
```

```
      RSQUAR1=(DIFF1/ICOUNT-F(1)/ICOUNT)/(DIFF1/ICOUNT)
      RSQUAR2=(DIFF2/ICOUNT-F(2)/ICOUNT)/(DIFF2/ICOUNT)
      WRITE(90,2090) RSQUAR1, RSQUAR2
2090    FORMAT(/' COEFFICIENT OF DETERMINATION for Stream Flow
     >        and WT=',2F10.3//)
       Endif
      Endif
     ENDIF
C
C --- Return
     RETURN
     END
```

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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